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STATUS OF POROUS BIOMASS SUPPORT SYSTEMS FOR WASTEWATER TREATMENT: AN INNOVATIVE/ALTERNATIVE TECHNOLOGY ASSESSMENT

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16. ABSTRACT

A study was conducted to assess the emerging wastewater treatment technology of porous biomass support systems (PBSS). These systems use large numbers of small, open-cell or reticulated polyurethane foam pads to support high concentrations of biomass in an aeration basin. The technology is being marketed by Simon-Hartley Ltd. in England (CAPTOR) and Linde AG (Linpor) in West Germany.

Visits were made to laboratories of the original process developers in the United Kingdom and in West Germany. Data were gathered through interviews with academic and commerical investigators in both countries and through a review of all available literature and data, both published and unpublished.

The study concluded that PBSS technology does not presently qualify as a fully developed technology, but that the technology offers some attractive potential benefits and very little risk for some intended applications. Thorough pilot plant and full-scale studies are needed to answer many remaining questions about the process and to provide design data and guidance.

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FOREWORD

The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water systems. Under a mandate of national environmental laws, the agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. The Clean Water Act, the Safe Drinking Water Act, and the Toxic Substances Control Act are three of the major congressional laws that provide the framework for restoring and maintaining the integrity of our Nation's water, for preserving and enhancing the water we drink, and for protecting the environment from toxic substances. These laws direct the EPA to perform research to define our environmental problems, measure the impacts, and search for solutions.

The Water Engineering Research Laboratory is that component of EPA's Research and Development program concerned with preventing, treating, and managing municipal wastewater discharges; establishing practices to control and remove contaminants from drinking water and to prevent its deterioration during storage and distribution; and assessing the nature and controllability of releases of toxic substances to the air, water, and land from manufacturing processes and subsequent product uses. This publication is one of the products of that research and provides a vital communication link between the researcher and the user community.

This report evalutes the technology of porous biomass support systems and the potential application of this process to biological wastewater treatment systems. This new technology offers some attractive potential benefits to wastewater treatment technology.

Francis T. Mayo, Director
Water Engineering Research Laboratory

ABSTRACT

A study was conducted to assess the emerging wastewater treatment technology of porous biomass support systems (PBSS). These systems use large numbers of small, open-cell or reticulated polyurethane foam pads to support high concentrations of biomass in an aeration basin.

Visits were made to laboratories of the original process developers in the United Kingdom and in West Germany. Data were gathered through interviews with academic and commercial investigators in both countries and through a review of all available literature and data, both published and unpublished.

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SECTION 1

INTRODUCTION

The Clean Water Act of 1977 and the Municipal Wastewater Construction Grant Amendments of 1981 include provisions that encourage the use of innovative and alternative (I/A) wastewater treatment technologies. To identify candidate technologies that might qualify as innovative or alternative, technology assessments of developing technologies are required. These assessments provide technical feedback to the technology development community and to the Federal, state, local, and private agencies involved in using emerging technologies to enhance the quality of the Nation's waters.

One of the emerging technologies selected by the U.S. Environmental Protection Agency (EPA) for assessment is porous biomass support systems (PBSS). These systems use large numbers of small, open-cell or reticulated polyurethane foam pads to support high concentrations of biomass in an aeration basin. The basic technology has been developing along two different lines. The British developer, Simon-Hartley, Ltd., has concentrated on external pad cleaning devices to waste the excess biomass in an effort to avoid the use of secondary clarifers in some applications of the process. The West German developer, Linde AG, has chosen to forego external pad cleaning and has developed their process more along the lines of conventional activated sludge treatment. In their process, they grow biomass both on the pads and in suspension. The function of the pads is to retain a large quantity of biomass in the aeration basin, thus reducing the solids loading on the secondary clarifiers and maintaining a higher effective mixed liquor suspended solids (EMLSS) concentration than could be maintained without the use of the pads.

To accomplish this assessment, visits were made to the laboratories of the original process developers in the United Kingdom and in West Germany, and the status of research and development efforts was discussed with academic and commercial investigators in both countries. Several pilot-scale and full-scale development projects were also visited in both countries during this visit. Two pilot-scale systems and one small industrial-scale system in the United States were also visited as part of this assessment. All available literature and data, both published and unpublished, were reviewed. This report is the result of these efforts, most of which took place during the spring and summer of 1984.

SECTION 2

CONCLUSIONS

Based on the visits to operating facilities and the review of all the available data, we have concluded that PBSS technology does not presently qualify as a fully developed technology. Definite risks are associated with adopting it for several of the applications for which its developers intended it. On the other hand, the technology offers some very attractive potential benefits and very little risk for some intended applications.

The manufacturers and suppliers of PBSS technology would never recommend installation of a system at present without thorough pilot plant investigation to provide design data and guidance. As a result, adoption of the technology on a full scale will proceed slowly, but it should not be marred by spectacular failures. The really promising applications of PBSS at this time appear to include:

1. Pretreatment systems for high-strength industrial waste,
2. Upgrading overloaded activated sludge plants, especially those that are habitually plagued by filamentous bulking, and
3. Addition to existing systems to produce nitrification without the need for additional clarifers.

SECTION 3

RECOMMENDATIONS

GENERAL

The Linpor-C system (Section 4) appears almost ready to become classified as one of the regular members of the available spectrum of biological treatment systems capable of consistently meeting secondary treatment requirements. Two full-scale field projects near Munich have demonstrated the efficacy of the Linpor C concept for upgrading existing municipal wastewater treatment plants (Section 5). The Captor process, used as the sole biological process without final clarifiers, is not ready to become so classified. Both systems require extra attention to the quality and reliability of preliminary and primary treatment processes to avoid severe operation and maintenance problems with pad cleaners (Captor) and retaining screens (both processes). Furthermore, design requirements to ensure proper mixing and distribution of porous biomass support (PBS) particles need to be better defined. Porous biomass support system (PBSS) technology should be treated as an innovative technology with a degree of risk that varies with the specific application. PBSS projects receiving consideration for I/A funding should be those for which the risks are minimized through careful consideration of the specific details of the project. As the technology continues to evolve and be better understood, it should be possible to attempt some projects with higher risk factors, providing that high potential benefits are possible as well.

FURTHER R & D EFFORTS

A tremendous number of questions about PBSS's remain. Answers to these questions could increase the attractiveness of this technology to potential users. Some of the research and development areas that have been pinpointed through the work of this technology assessment are discussed in the following sections.

The Porous Biomass Supports

Very little remains to be done in this area. We assume that the foam manufacturers will continue to look at new materials that might result in less pad wear and hence an improvement in system economics. The Captor pad dimensions and pore size characteristics have evolved as about optimum for this process, so few changes, if any, are foreseen for these. As the Linpor pads do not have to be handled in the same way as the Captor pads, it is conceivable that they might be altered somewhat to try to improve the cost-effectiveness of this system. For example, although the Linpor pads must be large enough to be retained by screens, they could easily be of random shape and not necessarily cut to size, as they are at present. Such a shift in manufacture might result in lower cost for the pads.

One very interesting possibility for basic research would be the use of specially manufactured or pretreated pads for enhanced removal of toxic or other materials when PBSS's are used as the first stage of a multi-stage biological system. A simple example would be the pre-coating of pads with a polyelectrolyte after pad cleaning to enhance the removal of suspended solids or to assist in colonization during system start-up.

Biomass Properties

A need exists for substantial fundamental research on the characteristics of PBSS biomass. The first basic question concerns the physiological equivalence of biomass contained within porous supports and freely suspended biomass at identical loadings. Inherent differences may exist in the distribution of physiological states between PBSS's (especially Captor) and activated sludge because of the equal and independent probability of wasting sludge of any age with conventional activated sludge and the (potentially) higher probability of wasting younger biomass from a PBS particle. This assumption presumes that the younger biomass is always found near the surface of the pad and that the older, more mineralized biomass will be found at the interior. With the development of highly effective pad cleaners, this could cease to be of any concern.

The following areas also need intensive evaluation: the effect of pad cleaning rates on biomass physiology, specific substrate uptake, biomass sludge yields, sludge dewaterability, diffusional resistance to oxygen and substrate transport, biomass hold-up, free suspended solids, and fluidizing properties of PBS particles. Similar attention should also be paid to Linpor systems in which PBS particle biomass hold-up is in equilibrium between growth and hydraulic attrition.

Pad Cleaning

Although sludge concentrations of 4 to 5 percent have been achieved in pad squeezing during several laboratory and pilot plant studies, it has been difficult to reproduce these results routinely in full scale. Modifications to the pre-squeeze roller system are currently being studied to help bridge this gap. The current thinking is to replace the pre-squeeze roller with a belt stretched between two rollers to increase contact time for the pre-squeeze function in hopes of removing more interstitial water.

Substrate Uptake

The independent parameters that influence substrate uptake and removal for conventional suspended growth systems will likely influence PBSSs. Unfortunately, to date, no definitive variable or set of variables have been defined as a predictive parameter. Volumetric loading and hydraulic residence times are currently used. Efforts to use F/M or SRT have not yet been entirely successful. A part of this problem is the analytical determination of active biomass from the particles. Additional development of effective standardized procedures of measurement are important in solving this problem. The role of diffusion in process performance is also critical. Evidence from pilot plants suggests the importance of diffusional transport of oxygen in nitrification processes. Similar phenomena are likely to exist in carbonaceous systems as well. The impacts of bulk substrate and oxygen concentration, particle characteristics (pore size, dimensions), hydraulic regime, biomass hold-up, and reactor temperature among others on substrate uptake may provide leads as to the importance of diffusion in PBSS's.

Finally, some data are needed to indicate the level of sensitivity of PBSS's to reactor temperature, pH, toxic shock, and hydraulic and organic shock.

Air Flow Requirements

Air from submerged diffusers provides oxygen to support basic biomass respiration and provides turbulence to mix and distribute PBS particles. Off-gas oxygen transfer studies under process conditions must be conducted in order to effectively evaluate the rate of mass transfer of oxygen to PBSS's. Process conditions under which these tests are conducted must be such as to provide proper PBS particle distribution. Mass transfer comparisons between PBSS's and conventional suspended growth systems must be made under process conditions which are optimal for each system if they are to be meaningful in any kind of economic or energy audit.

The effective distribution of PBS particles in the reactor is of paramount importance to the success of this process. Every indication is that this can be achieved in diffused air systems if proper downflow regions are created. Pad distributions may also be effectively mixed by mechanical means. Mechanical power inputs to properly distribute pads may be lower than those used in diffused air systems. To date, no definitive research has been performed to assess the economic value of mechanical pad distribution.

Currently, there is research under way on PBS particle mixing with air in both West Germany and the United Kingdom. Investigators at the Water Research Centre in the U.K. also indicate that oxygen transfer studies will take place at Freehold in the near future.

Sludge Settling Properties

The West German experience has been favorable with respect to improving biomass settling properties with PBS particle additions. Whether the particles improve biomass SVI by virtue of reducing reactor F/M, by changing the predominant suspended growth population via attrition of more settleable biomass or by some other phenomenon is not entirely clear at this time. Side-by-side full-scale studies at plants with endemic sludge settling problems would be useful. One such study at Freising, West Germany is under way at this time, but experimental control at this facility is uncertain.

Further basic research on biomass properties in Linpor-type systems may also be very useful for better describing what has been seen in West Germany.

In concert with biomass settling is the effect of PBSS on the design of final clarifiers. Information on the settling and thickening properties of the freely suspended biomass from PBSS (Captor and Linpor) would be most useful.

SECTION 4

TECHNOLOGY DESCRIPTION

BRIEF SUMMARY DESCRIPTION

The general class of wastewater treatment processses falling into the category of porous, biomass support systems (PBSS's) have a singular common denominator. They all exploit the natural ability of microorganisms commonly found in wastewater treatment plants to colonize the surfaces and cavities of inert materials when such materials are contacted with wastewater. In their current stage of commercial development, PBSS's employ large numbers of small (ca. 1.5 cm^3 to 8 cm^3) open cell or reticulated polyurethane foam pads* of very high porosity (ca. 95% to 97%). The pad material has a specific gravity very near that of water, so by inducing the correct flow patterns in a basin, the pads can be mixed and circulated within the basin. Figure 1 shows some of the pads and Figure 2 shows the pads in an aeration basin.

As the pads move through the wastewater, the wastewater also moves through the pads, bringing nutrients, oxygen and particulate matter into contact with the biological growth which may be either attached to the pad material or entrapped within the pores. The most obvious advantages of such a system, assuming the use of screening devices to prevent pads from leaving the basin, are:

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*In the literature being developed on this subject, the biomass support pads are also referred to as particles and elements. The letters BSP, standing for biomass support particles, have sometimes been used.

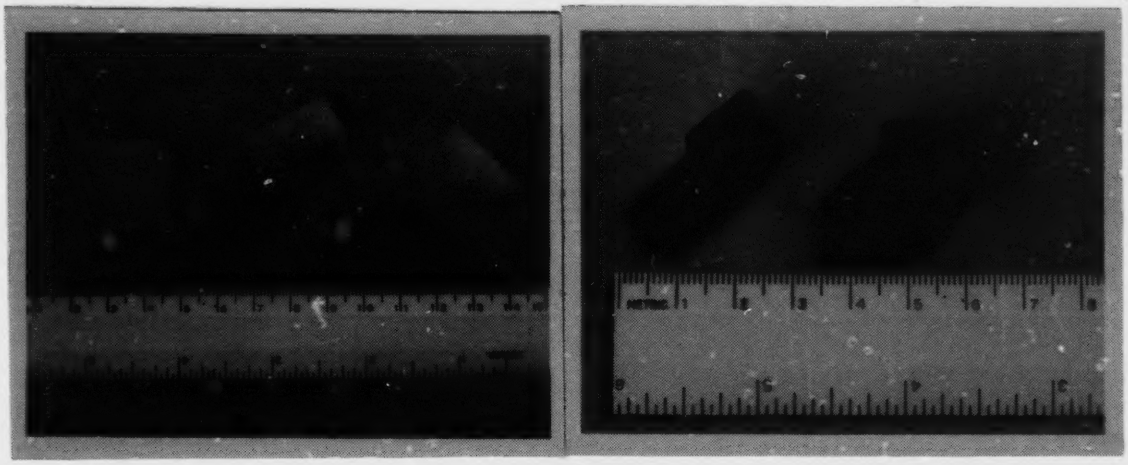

Figure 1. Typical porous, biomass support pads.
Left photo - Captor pads, 25mm x 25mm x 12mm
Right photo - Linpor pads, 15mm x 12mm x 12mm

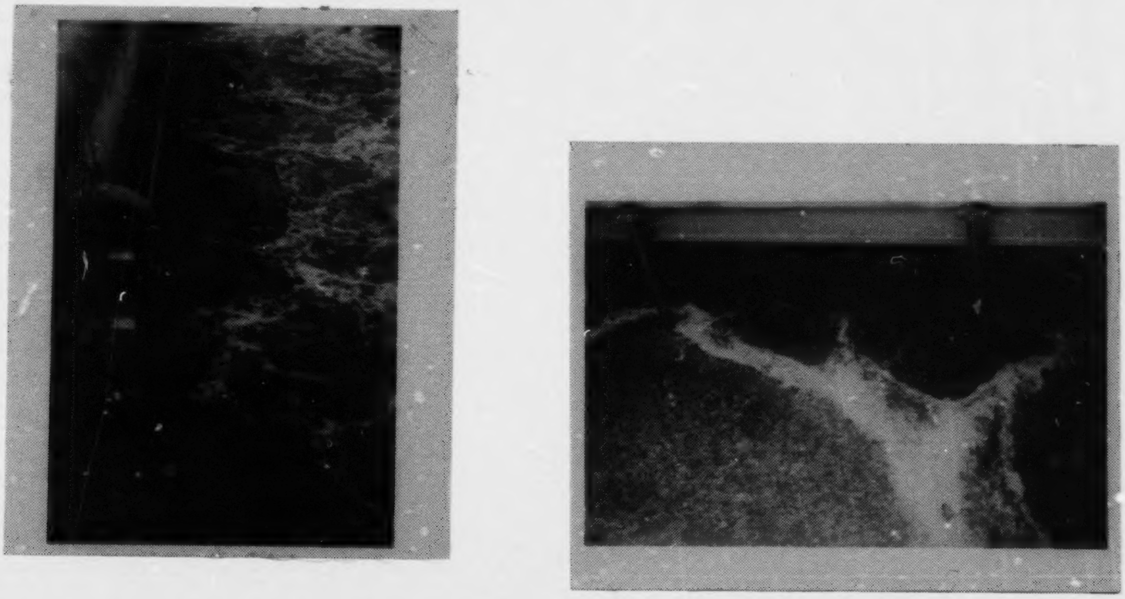

Figure 2. Aeration basin containing pads at a volume concentration of 30 percent.

1. The maintenance of high biomass concentrations within the aeration basin. The pads have been used successfully at volume concentrations of up to 40 percent and have been colonized, in field installations, at biomass concentrations up to 40 g/L (based on pad gross volume), giving an "equivalent" biomass concentration of 16,000 mg/L, neglecting any biomass in the free liquid phase. More typically, equivalent biomass concentrations are expected to be in the 7,000 to 10,000 mg/L range. Under conditions of very low strength wastewater, biomass levels may decrease to the 3,000 to 4,000 mg/L range.

2. The absence of a need for recycling microorganisms to the aeration basin in order to maintain a given level of biomass.

3. The removal of a thickening constraint from final clarifier design and in fact, in certain applications, the elimination of the need for the final clarifier at all.

Other advantages, both potential and/or observed, may be realized in specific applications of the technology. These will be introduced in subsequent sections.

To date, two somewhat different paths of development of the basic concept outlined above have occurred. The Captor Process, marketed by Simon-Hartley, Ltd. (Ashbrook-Simon-Hartley in the USA), was developed from research by Dr. Bernard Atkinson and his colleagues at the Department of Chemical Engineering, University of Manchester Institute of Science and Technology (UMIST) and is being commercially developed with technical assistance from the Water Research Center, Stevenage, U.K. The Linpor Process is being developed by Linde AG in West Germany from in-house research conducted by Dr. Hans Reimann and Uwe Fuchs. Linde AG has had technical assistance from the Technical University of Munich at Garching.

THE CAPTOR PROCESS

Basic Process Description

The pads are reticulated (substantially all windows removed) polyurethane foam, cut to cuboidal form with dimensions of (closely) 25 mm x 25 mm x 12.5 mm. Pore size is controlled through manufacture at dimensions which result in approximately 11.8 pores per lineal centimeter (30 per inch) with a porosity of 97 percent. Laboratory studies have indicated that these gross dimensions and internal characteristics are about optimum for the Captor concept (see Section 3).

The normal design level for pad concentration is 40,000 per m^3, a volume concentration of 31 percent. This concentration has been determined to be near the practical limit for consistent mixing without special provisions in both pilot- and full-scale trials. In practice to date, pad concentrations ranging all the way from 16,000 to 43,000 per m^3 have been successfully used.

In the basic Captor process, shown in Figure 3, settled primary effluent enters the aeration basin with its complement of pads. Depending upon the strength of the wastewater, a certain level of biomass will become established in and on each pad. Current experience indicates that this may be from 60 mg to 300 mg per pad, giving an "equivalent" mixed liquor suspended solids concentration (neglecting non-pad solids) of from 2,400 to 12,000 mg/L (at a pad concentration of 40/L). Typical target levels are 7,000 to 10,000 mg/L.

To provide the balance between growth on the pads and wasting, pads are withdrawn from the aeration basin at some pre-determined rate and most of the accumulated biomass is removed by a pad cleaner, as shown schematically in Figure 4.

As the pads move up the conveyor (at a rate of about 2,400 per minute on a 300 mm (12-inch) wide belt), some interstitial water, practically solids-free, is drained from the pads by gravity. Additional solids-free water is removed by a pre-squeeze roller at point 3 in Figure 4. The compressible pads are

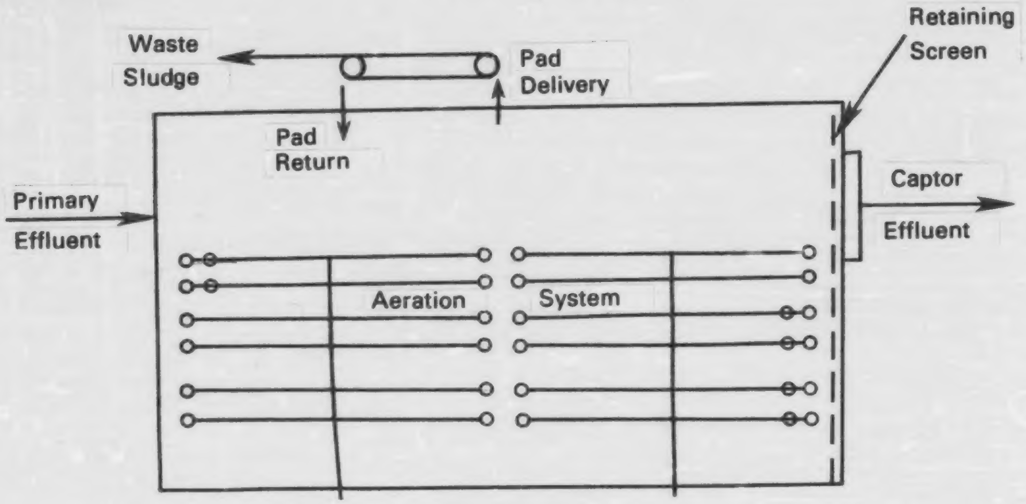
Waste
Sludge
Pad
Delivery
Retaining
Screen
Pad
Return
Primary
Effluent
Captor
Effluent
Aeration
System

Figure 3. Flow schematic - basic Captor process.

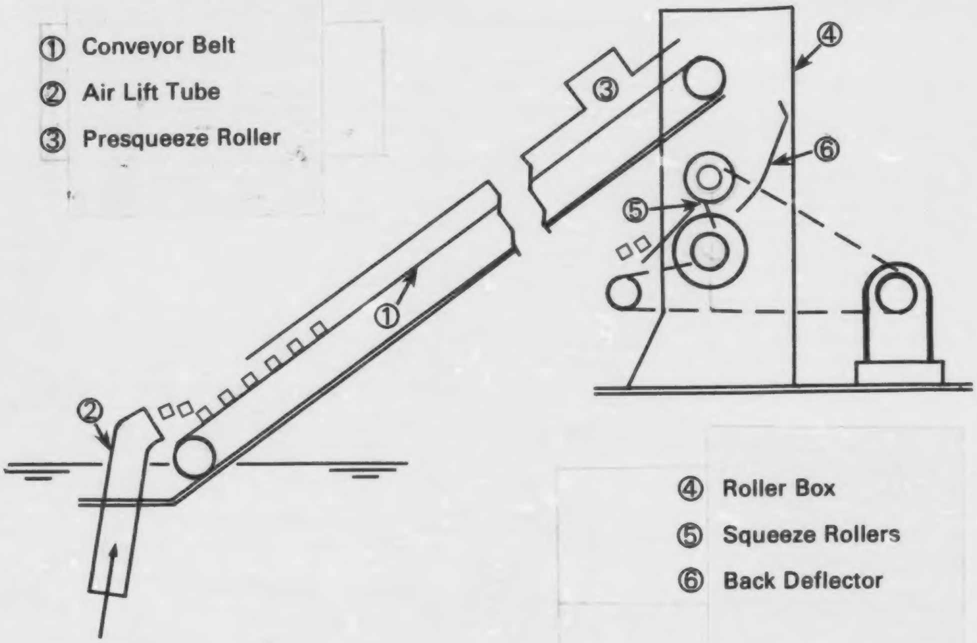
① Conveyor Belt
② Air Lift Tube
③ Presqueeze Roller
④ Roller Box
⑤ Squeeze Rollers
⑥ Back Deflector
①
②
③
④
⑤
⑥

Figure 4. Diagram of Captor pad cleaner.

then squeezed hard between two rollers (point 5 on Figure 4), which removes the now-concentrated biomass at up to 4 to 5 percent (dry) solids under favorable conditions. Lower concentrations have been observed in practice, generally because of weak wastewater and low pad solids levels. The sludge is diverted from the process by gravity flow or by pumping, and the cleaned pads are returned to the aeration basin to accumulate more biomass.

Pads cannot be allowed to leave the aeration basin with the treated wastewater, thus some restraint, in the form of screens, is required across the exit of the basin. The screen openings must be small enough to prevent passage of pads but large enough to allow passage of most smaller-dimensioned particles in order to avoid blockage, requiring excessive maintenance. In addition, there needs to be sufficient screen area to prevent velocities which are high enough to hold large numbers of pads on the screen surface. Trial-and-error development has resulted in the adoption of 4-mesh screens (5.13-mm square apertures), large enough to limit the peak hydraulic loading to less than 78 m^3/m^2-h based on gross submerged screen area.

Aeration system design has proven to be a much more critical element for the success of the Captor process than for conventional activated sludge. The development work has clearly shown the necessity of producing discrete upward and downward currents which are strong enough to counter the buoyant characteristics usually displayed by the pads. Thus a proper arrangement of diffusers on the tank bottom is vital for producing the mixing pattern necessary to keep the pads suspended and moving through the liquid. This has proven even more critical when fine bubble diffuser systems are employed for aeration and in aeration basins of high aspect (L/W) ratio. In the latter, spiral roll patterns have proven superior. For a given successful diffuser configuration, there is also a lower and an upper limit on air flow rate. Based upon basin floor area, the presently accepted range of air flow rates is 100 L/min-m^2 to 300 liters/min-m^2. Less air flow than 100 L/min-m^2 allows "dead" spots and encourages either settling or floating (or both) of large numbers of pads. More air flow than 300 L/min-m^2 creates too much shear on the pads, preventing accumulation of the optimum amount of biomass per pad for cleaning purposes. Depth of the basin may be an important element and is currently being investigated as it affects aeration and mixing.

Effluent from the basic Captor process (Figure 3) may follow one of several possible routes. These include:

1. Discharge to a municipal sewer if Captor is being used as industrial pretreatment process.

2. Discharge to a subsequent treatment process of another type, e.g., activated sludge, facultative lagoons or a land-based treatment system if Captor is being used as an upgrading or load reduction process.

3. Discharge to another Captor stage if Captor is being used as a multi-stage complete treatment system.

This is certainly not an all-inclusive list. In addition, modifications to the basic Captor flow diagram are also possible and may show some advantages. Some of the more obvious ones, suggested by other successful processes, are presented in the next section. At present none of these has been the subject of any bench-scale or pilot-scale study.

Captor Process Modifications

Effluent Polishing and Nitrification--

The flow schematic for this modification is shown in Figure 5. The initial, carbonaceous BOD removal process could be of any type, including Captor. If it was Captor, there simply is not enough background data available to rule out the need for an interstage clarifer; thus it is shown in the diagram as typical for any process. Based upon recent WRC results, no clarifier would be needed after the polishing and nitrification stage, primarily because of the low-yield coefficients associated with the nitrifying bacteria. The ability to accumulate a relatively high concentration of nitrifiers in the pads and to "absorb" an increment of suspended solids could make this modification competitive with many nitrification - effluent filtration schemes.

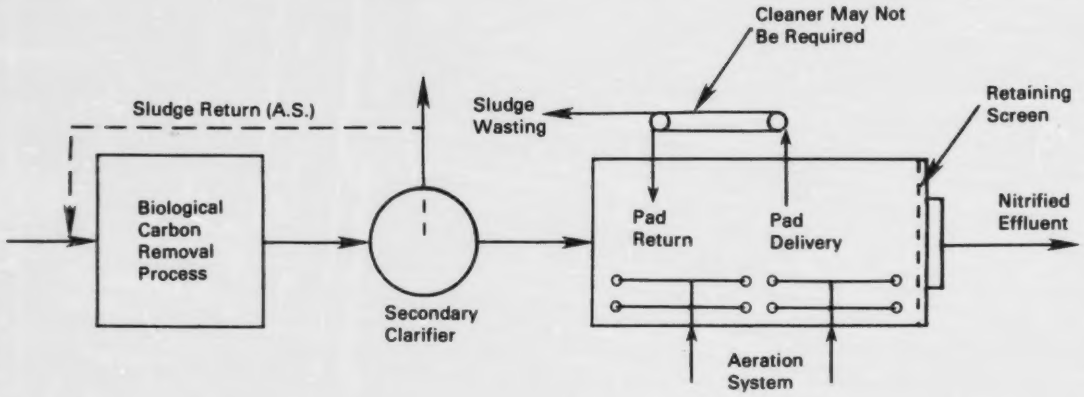
Cleaner May Not Be Required
Sludge Return (A.S.)
Sludge Wasting
Retaining Screen
Biological Carbon Removal Process
Pad Return
Pad Delivery
Nitrified Effluent
Secondary Clarifier
Aeration System

Figure 5. Effluent polishing and nitrification process using Captor.

Modified Solids Contact--

In the flow diagram shown in Figure 6, waste solids with a fairly high sludge age are added to a contact tank along with screened, de-gritted raw sewage. The effect is an enhanced removal of BOD and suspended solids in the subsequent clarifier. The clarifier overflow becomes the feed to the Captor process. The clarifier underflow would, of course, be a particularly unstable sludge and would have to be stabilized by either anaerobic or aerobic digestion. This modification may have some advantages over the basic Captor flow diagram for pre-treatment of certain strong industrial wastes. The contact and clarification could be accomplished in a clarifier of the flocculating feedwell design.

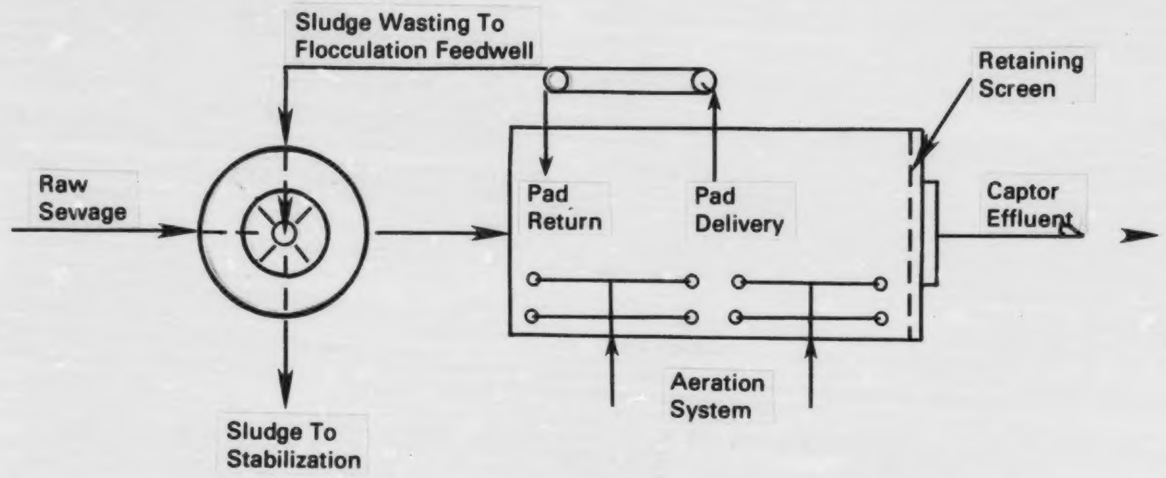
Sludge Wasting To
Flocculation Feedwell
Retaining
Screen
Raw
Sewage
Pad
Return
Pad
Delivery
Captor
Effluent
Aeration
System
Sludge To
Stabilization

Figure 6. Modified solids contact process using Captor.

Miscellaneous--

Additional modifications which have been suggested to date include:

1. Use as an adjunct to batch sequencing reactors, and

2. To increase the biomass in mixed anaerobic reactors treating (predominantly) soluble wastewaters.

THE LINPOR PROCESS

Linpor-C

The pads used in the Linpor process are a bit more heterogeneous in size and shape and manufactured to less exacting standards than those used in the Captor process, for reasons which will soon be made clear. The process developers, Linde AG, have the same concerns as Simon-Hartley Ltd., however, relative to pad wear and pad life expectancy, and a great deal of attention is paid to this aspect of pad manufacturing. Less attention is given to final dimensions. An "average" pad is a parallelepiped with dimensions about 12 mm x 12 mm x 12 mm. Some pads may have a dimension down to 10 mm and others may have a dimension up to 17 mm. The pads are of open cell type foam and have a pore size somewhat smaller than Captor pads, usually running about 15 to 20 per lineal centimeter (38 to 50 per inch). In terms of the volume concentration of pads used, the Linpor process may employ from 10 to 40 percent. Most of the present investigations are being carried out near the upper level of 40 volume percent.

Just as in the Captor process, screens are needed across the aeration basin exit to prevent loss of the pads. To this point the two processes appear almost identical. However, the Linpor process employs no external pad cleaning device, representing a radical departure from Captor. The Linpor process relies upon the turbulence and shearing action in the aeration basin to control the amount of biomass fixed in and on the pads. Biomass in excess of this amount exists as freely suspended floc particles. In the Linpor-C process, shown in Figure 7, where the objective is carbonaceous BOD removal, these freely suspended flocs represent a substantial amount of both BOD and suspended solids. Thus a secondary clarifier is necessary if good quality effluents are to be produced. As long as the clarifier must be included, one might as well recycle biomass to the aeration basin to further increase the treatment capacity, and this is part of the Linpor-C process.

Typically, as in Captor, there might be 8 to 15 g/L of biomass associated with the pads in Linpor. In addition, there might be 2.5 to 4 g/L of biomass associated with the free liquor phase at steady state. Using 8 g/L and 3 g/L, respectively, as representative values, and a pad concentration of 40 percent by volume, the resulting "effective" mixed liquor suspended solids (EMLSS) concentration would be (see Tables 1, 2, and 3)

$$(8 \times .4) + (3 \times .6) = 5 \text{ g/L } (5{,}000 \text{ mg/L}).$$

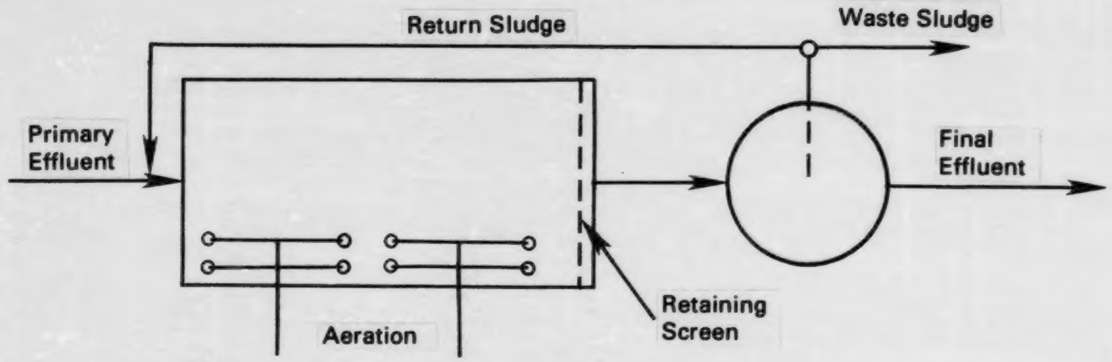

Figure 7. Flow schematic, Linpor - C.

This may not appear to represent a significant improvement over activated sludge processes (unless both the pad and non-pad solids could be increased, which experience shows is an attainable goal), however, there are other important considerations. The most obvious relates to the differences in secondary clarifer capacity required for an activated sludge process operated at a MLSS level of 5,000 mg/L as opposed to one operated at 3,000 mg/L (as the latter value is what the Linpor clarifier will "see"). Also, and this can only be learned from an analysis of actual Linpor system performance data (refer to Section 5), the sludge volume index (SVI) of the solids wasted from a Linpor system is considerably lower than that of a side-by-side activated sludge plant treating the same wastewater at a comparable food-to-microorganism (F/M) loading. The combination of the above factors will result in either a reduction in clarifier volume for equivalent effluents or a better Linpor effluent at equivalent clarifier capacity.

Linpor-N, Effluent Polishing and Nitrification

This idea was actually the first application conceived for the foam pads during the development work by Linde AG. The flow diagram is shown in Figure 8. Any biological process which can reduce the BOD to the 20 to 30 mg/L range without oxidizing nitrogen may be used as the first step. The second step is Linpor, operated at 20 to 40 volume percent pads and a hydraulic residence time of 2 to 4 hours. The dissolved oxygen must be maintained in the 4 to 5 mg/L range at a minimum, as the nitrification rate appears to be dependent upon dissolved oxygen concentration below this level when the nitrifying biomass is fixed within the pads. No clarifier is needed downstream of the Linpor-N reactor.

Miscellaneous--

The Linpor process has also been suggested as an adjunct to well-mixed anaerobic reactors treating predominantly soluble wastes. A pilot system has been operated on winery wastewaters.

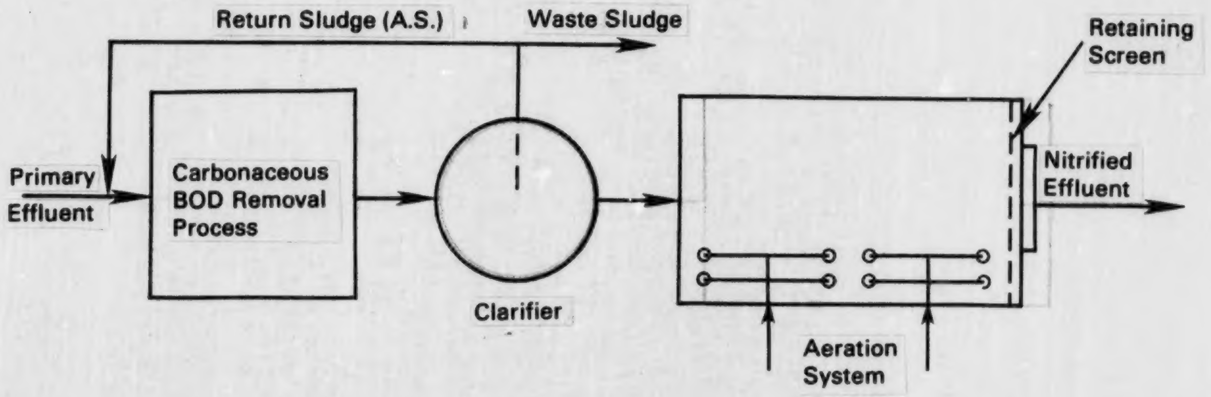
Return Sludge (A.S.)
Waste Sludge
Retaining Screen
Primary Effluent
Carbonaceous BOD Removal Process
Clarifier
Nitrified Effluent
Aeration System

Figure 8. Flow schematic, Linpor - N.

SECTION 5

DEVELOPMENT STATUS

SUMMARY OF RESEARCH FINDINGS

U.K. Experiences - UMIST/Simon-Hartley Ltd.

Much of the early development work with PBS particles was performed at the University of Manchester (UMIST), U.K. Detailed descriptions of this early work are delineated in Section 6. As a result of this early work, a patent was applied for and granted in the U.K. (1) and later in the U.S. (2) by UMIST and Simon Hartley Ltd. for the application of porous supports (called Captor) for the treatment of municipal and industrial wastes.

Walker and Austin (3) reported on preliminary work performed by Simon-Hartley Ltd. to assess the potential of PBSS for wastewater treatment. Initial work was performed in 0.6 m^3 pilot columns, 0.5 m in diameter and 3.5 m high. PBS particles studied included polypropylene toroids with a specific gravity of 0.91 and porosity 92 percent; polypropylene pads of several thicknesses with porosities ranging from 95 to 97 percent; and plastic foam pads with a specific gravity of 1.1 and porosity of 97%. Samples of wastewaters from two domestic sites were used as influent to the pilot units.

This early research with PBS particles indicated that the lighter-than-water polypropylene particles had undesirable fluidization properties and were often found packed at the top or bottom of the column. The more porous polypropylene particles produced somewhat more favorable fluidization properties due to the higher gross densities of the particles. Low biomass hold-ups were obtained, however, with the higher porosity pads due to the small pore sizes (approximately 2.9 g dry weight/L of pad volume versus 8 g/L for the toroids). The more dense plastic foam pads produced the best "fluidization" properties of the particles studied and the particles "retained sufficient biomass of high activity." No data on particle biomass hold-up were actually presented, however. The study also indicated that the biomass mineralized within the pad structure over time, and it was felt that in order to maintain an effective biomass activity, cleaning of the PBS particles was necessary. Squeezing of the plastic foam pads produced a sludge of about 4 to 6 percent.

Extensive studies were performed by Simon-Hartley to perfect the properties of the PBS particle and to evaluate important process control variables (4). Detailed experimental studies were not published in the scientific literature, however. A reticulated polyurethane foam particle, 25 mm x 25 mm x 12.5 mm in size with 97% void volume was eventually found to possess excellent properties of wear, "fluidization," biomass hold-up, and "squeezability." In-house studies led to preliminary recommendations relative to aeration and mixing requirements, oxygen transfer, screening, cleaning, and performance capabilities. These parameters were subsequently used to design pilot studies at Freehold, U.K., which are reported in Section 5. In parallel with the pilot work at Freehold, the Water Research Centre is currently performing pilot studies to better evaluate particle integrity, mixing requirements and biomass properties. These results are not yet available for review.

West Germany - Linde AG

The use of PBS particles for wastewater treatment was apparently developed somewhat parallel to the UMIST/Simon-Hartley Ltd. studies by Linde AG/Technical University of Munich (5,6,7,8). Linde AG also adopted an open cell polyurethane foam which was somewhat more dense with smaller pores (38 to 50 pores/inch) than the Captor particles. The particle sizes used in both laboratory and field studies range from 10 to 15 mm in size, normally in the shape of a cube or parallelepiped.

The first application of PBS particles by Linde AG was for the purpose of nitrification (6,7). These nitrification experiments were conducted with a 1

m^3 reactor filled with PBS cubes to 37% by volume. No clarifier or sludge return were used in these studies. Influent to the unit was secondary effluent from a domestic wastewater treatment process. The results of this study are presented in Table 1. Effluent solids were always under 20 mg/L. Within four weeks of start-up, a high degree of nitrification had occurred. Over the experimental study of "some" months, no deterioration of particle biomass was noted. An equilibrium apparently was developed between growth and attrition in this system. Other pilot tests conducted at still another domestic treatment plant with lower PBS particle concentrations (24 to 35%) and higher influent TKN (24 to 60 mg/L N) at a hydraulic retention time of 1.1 hours produced about 80% TKN oxidation. No details of effluent solids, biomass hold-up or system stability were presented (5,6).

TABLE 1. PILOT PLANT RESULTS - LINPOR (6)

Parameter	Units	Experimental phases			
		1	2	3	4
Influent					
BOD	mg/L	16	16	27	9
TKN	mg/L	34.8	25.2	23.5	17.6
NO_3-N	mg/L	0.7	0.7	0.5	1.4
Effluent					
BOD	mg/L	7	6	12	8
TKN	mg/L	2	3.8	9.6	1.2
NO_3-N	mg/L	28.5	17.4	9.8	19.0
SS	mg/L	8	16.7	16	10
Hyd. ret. time	hrs	2.5	1.7	1.2	3.2
Temp. reactor	°C	14-17	15-19	15-18	16-20
DO reactor	mg/L	3-7	3-5	3-5	4-6
PBSP biomass	g/L	8.7	10.1	14.6	12.5
EMLSS	g/L	3.2	3.8	5.4	4.6
TKN load	kg/m^3 d	0.33	0.36	0.45	0.13

Pilot plant studies on nitrification are also being conducted at the present time at Abwasserzweckverband Munchen-Ost at Poing, West Germany by Linde AG (7). Effective nitrification is being achieved in this pilot unit, which receives secondary effluent from the domestic wastewater treatment plant. Results of pilot plant experiments at this facility to date are presented in Table 2. Six experimental studies were conducted using Linpor pads at a volumetric concentration of 30 percent. NH_4-N loadings ranged from 0.37 to 0.65 kg/m^3 d and PBSP biomass concentrations ranged from 13 to 15.7 g/L. Of substantial interest in these studies was the finding that dissolved oxygen concentrations played an important role in the nitrification process, likely due to diffusional limitations. DO values above 5 mg/L were required to achieve effective nitrification.

TABLE 2. PILOT PLANT RESULTS - LINPOR N (7)

Parameter	Units	Experimental phases 1	2	3	4	5	6
Influent							
BOD_5	mg/L	21	23	21	25	17	16
NH_4-N	mg/L	56	69	63	65	73	67
Effluent							
BOD_5	mg/L	9	13	17	17	12	10
NH_4-N	mg/L	4	19	35	32	7	15
Hyd. ret. time	hrs	3.5	3.7	4.1	3.3	3.5	2.5
Temp. reactor	°C	19	16	20	18	20	20
DO reactor	mg/L	5.3	5.6	2.2	3.8	5.9	5.7
PBSP biomass	g/L	14	13	15.7	15.7	14.7	14.3
EMLSS	g/L	4.2	3.9	4.7	4.7	4.4	4.3
NH_4-N load							
Volumetric	kg/m^3 d	.39	.44	.37	.47	.50	.65
Biomass	kg/kg EMLSS d	.09	.11	.08	.10	.11	.15

The second general type of experiments conducted by these investigators have dealt with PBS particle addition to aeration tanks for the purpose of intensifying biomass activity and improving effluent settling properties. PBS particles were employed in combination with suspended flocculent growths in aeration basins. Clarification and sludge return were employed as in conventional activated sludge processes (Linpor-C).

Hegemann and Englmann (6) reported on several pilot plant studies at domestic treatment facilities in West Germany. A 1-m^3 pilot plant filled with 40 percent by volume of PBS particles was operated at one site (F). The results of these different pilot test runs with increasing volumetric loading are presented in Table 3 along with average results of full-scale plant operation without PBS particles. Two important features of PBS particles can be observed from these tests. First, the addition of the PBS particle to the aeration tank substantially increased the reactor biomass concentration. This effectively reduced the F/M ratio for a given volumetric loading. Second, the addition of the PBS particles dramatically reduced the SVI of the reactor suspended solids. Both features contributed to an improved effluent.

TABLE 3. LINPOR-C TEST RESULTS AT SITE F (6,8,9)

Test	Volumetric load kg/m^3 d	MLSS mg/L	PBSP biomass mg/L	EMLSS mg/L	F/M kg BOD/kg d	SVI mL/g	BOD_5 eff. mg/L
Pilot tests (PBSP)*							
1	1.94	3420	8570	5480	.35	129	16
2	2.62	3700	8100	5160	.51	130	16
3	3.86	3060	9200	5510	.69	128	27
4	1.22	3260	8790	5470	.22	162	9
Full-scale plant							
No PBSP	1.13	2580	--	2580	.47	485	48
With PBSP†	1.70	3920	12,700	5680	.30	130	7

*Linpor cubes, 40% by volume in pilot tests.
†Linpor cubes, 20% by volume in full-scale study.

These authors found similar results at another domestic wastewater treatment facility. Parallel tests in 20-L pilot units with and without PBS particles indicated lower F/M, lower SVI and superior effluent BOD_5 in the plant containing 40 percent by volume PBS cubes. They reported PBS particle biomass hold-up values of 15 g/L in these tests (6,9).

In another test series, side-by-side experiments were conducted over a 12-month period to evaluate the long-term stability and effectiveness of PBSS's. The pilot plant used at city M employed an aeration tank with a volume of 6 m^3. The tank was filled with 30% by volume of PBS cubes. The full-scale plant did not receive PBS particles but was operated at approximately the same volumetric loading. Results of this study appear in Table 4. As was found in the previous tests, the addition of PBS particles effectively reduced F/M for the same volumetric load and reduced SVI as compared with the full-scale plant.

TABLE 4. LINPOR-C TEST RESULTS AT SITE M (8,9)

Test	Volumetric load kg/m^3 d	MLSS mg/L	PBSP biomass mg/L	EMLSS mg/L	F/M kg BOD/kg d	SVI ml/g	BOD_5 eff. mg/L
Pilot tests (PBSP)*							
2b	2.34	4640	9,950	6180	.41	148	15
3	3.07	4290	13,210	6830	.45	128	13
Full-scale plant (no PBSP)							
2b	2.06	2520	--	2520	.88	222	24
3	2.12	2160	--	2160	.98	188	10

*Linpor cubes, 30% by volume in pilot tests.

It is significant to note the observations of these West Germany investigators relative to the PBS particle biomass. Hegemann and Englmann (6) reported that an equilibrium was reached after a period of several weeks between biomass growth and attrition. Furthermore, they indicated, as did Reimann (8), that no loss in biomass activity, as measured by specific oxygen uptake rate, was noted up to 12 months of continuous operation without pad removal. Our observations of two full-scale plants in operation for many months (Freising and Munich I) indicated that PBS particle biomass was fresh and dark brown throughout the particle volume. There were no signs of anaerobosis or mineralization within the pad structure.

Although comparisons between pilot-scale and full-scale performance are not directly one-to-one and considerably more full-scale experience is warranted, these early West Germany studies do demonstrate two important characteristics of PBSS's which make them likely candidates for treatment plant upgrading.

Currently, there are at least two full-scale studies using Linpor-C being conducted in West Germany. At Freising, Linpor particles (25% by volume) have been added to one tank for the primary purpose of reducing SVI. Currently, pads are now being added to remaining tanks. Results of this work will be available in 1985. Research at Munich I, which is being supported by the town and the federal government, is being conducted in both pilot plants and full-scale tanks. Results of this work will be available in the near future.

SUMMARY OF PILOT- AND FULL-SCALE FACILITIES

Experience in the United States

In the U.S., Captor experience is limited to two pilot plants, each operated for about four months, and one small-scale industrial system. While there are some valuable lessons to be learned from the U.S. experience, it would be grossly unfair to judge the potential of the Captor process on the basis of this experience alone. The pilot plant studies were not particularly well conceived or carried out. In neither case was there a well-defined control, as for example in the Freehold, U.K. studies, to compare Captor against. In one case (Marion, Illinois) the state regulatory agency informed the city and its consultant that Captor, being an untried process in the U.S., would not be considered for plant upgrading regardless of its performance at pilot-scale. This disheartening intelligence came just at about the time of system startup. It naturally had an adverse effect on the performance of the study, especially the quality of the analytical work.

At Downingtown, Pennsylvania, the Captor process was thwarted by the nature of the wastewater load, which concomitantly also caused severe problems for the existing activated sludge system. Extremely high infiltration/inflow and occasional slugs of toxic wastes, together with a peculiar periodic loading of starchy materials from a large commercial bakery, was sufficient to discourage the consultant charged with Captor evaluation.

The industrial installation is achieving excellent BOD and COD removals. However, it would be a mistake to attempt to evaluate this installation as a "pure" Captor process. Because of a poor initial aeration system design, most of the experience at this plant has been gained with the majority of the pads collected in a large floating raft at the surface of the aeration basin. Consequently, the bulk of the biomass has been in suspension rather than in the pads and was recirculated to the reactor from a conventional clarifier. The operation has been more akin to activated sludge than Captor.

Marion, Illinois--

This pilot plant consists of a Captor section in series with complete-mix activated sludge (CMAS). Both basins have a volume of 14.5 m^3 (512 ft^3); however, the hydraulic detention time of the CMAS section is 3.2 hrs, three times that of the Captor section. A constant feed rate of 3.78 L/sec (60 gpm) (determined by bucket and stop-watch measurement) is fed to the plant. Following the Captor section, 2.52 L/sec (40 gpm) is diverted to the effluent sump and 1.26 L/sec (20 gpm) receives second-stage biological treatment in the activated sludge section. This arrangement was selected because it simulated closely the design detention times which would have occurred in the Marion wastewater treatment plant if it was converted to a Captor-CMAS process flow scheme. The pilot plant was brought on-line in March of 1984 using primary clarifier effluent as feed. As sodium aluminate and polymer are added to the raw sewage to produce additional removals of suspended solids and BOD (to decrease the loadings to a faltering RBC system) and the Marion sewerage system receives substantial infiltration and inflow during the spring season, the strength of the pilot-plant feed was quite low during the first three months of operation. Extensive sampling and analysis was carried out during the first two months of operation. The Marion POTW is manned 24 hours per day using three shifts. Originally, the composite samples (see Figure 9 for sampling locations) were collected and analyzed by the second (afternoon) shift, whereas the first (day) and third (night) shifts collected grab samples only for analysis. During this initial testing period, observations made by the superintendent caused him to alter this schedule so that the composites were collected and analyzed by the first shift. Grab samples were collected and analyzed by the second and third shifts. Soon after start-up, a decision was made by the Illinois EPA that the Captor process would not be allowed to be used at Marion regardless of the outcome of the pilot-scale test program. This decision was evidently prompted by the severe problems experienced with the RBC system at Marion leading to a reluctance on the part of the state to approve any other innovative technology to replace one which had failed to live up to performance claims. At this juncture, testing of the pilot-plant was cut back to one shift per day (day shift). In addition to these complications, it should be mentioned that interviews with the laboratory staff showed that several other problems may exist relative to the data obtained from the pilot-plant operation. Although all the plant personnel involved in the testing program were "schooled" in proper procedures by a qualified professional chemist prior to the start-up of the pilot plant, there were inconsistencies noted among analysts on procedures and calculations, especially with regard to the BOD tests. There were also continuing problems noted with the quality of dilution water and the seeding techniques employed. All things considered, the accuracy of the BOD data is probably somewhat worse than that indicated as reasonable in Standard Methods (±15%), and numerous outright anomalies exist. For example, on many occasions total BOD values were substantially less than the soluble BOD value on the same composite sample. Where such obvious problems arose, the data for that day were not included in the "weekly" averages.

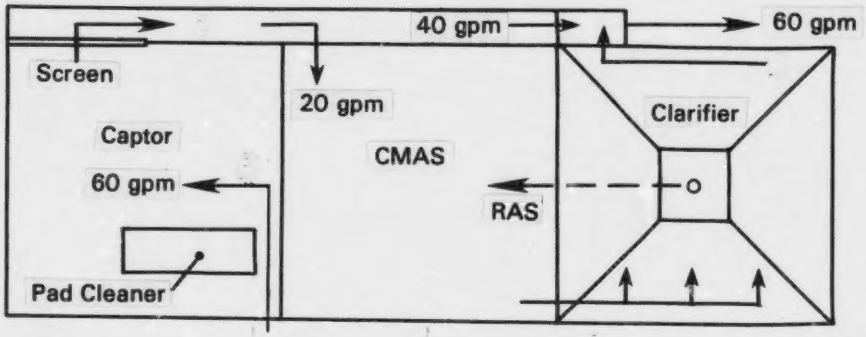

Figure 9. Marion, Illinois schematic.

Here, as in the case of Downington, "weekly" averages means an average of seven consecutive usable (believable) data points. The seven days are not necessarily seven consecutive days, as some data are missing and some are purposely omitted. Within these rather severe limitations, Figures 10 and 11 show the performance of the Captor section and the overall plant relative to total and soluble BOD removal.

As shown on the performance graphs, the pilot plant had a "full" (design) complement of pads (40/L) for only two of the eight weeks for which usable data exist. Pad solids during the entire period of operation were very low, ranging from 45 to 70 mg per pad. During the last few weeks of the study, with the wastewater temperature averaging 18°C (65°F), the pilot-plant performance was fairly consistent and is summarized in Table 5. During this period the F/M load to the Captor section ranged from 0.6 to 0.9 kg BOD/kg MLSS·d and that to the activated sludge section ranged from 0.09 to 0.13. The overall system effluent was excellent, averaging less than 5 mg/L of BOD and

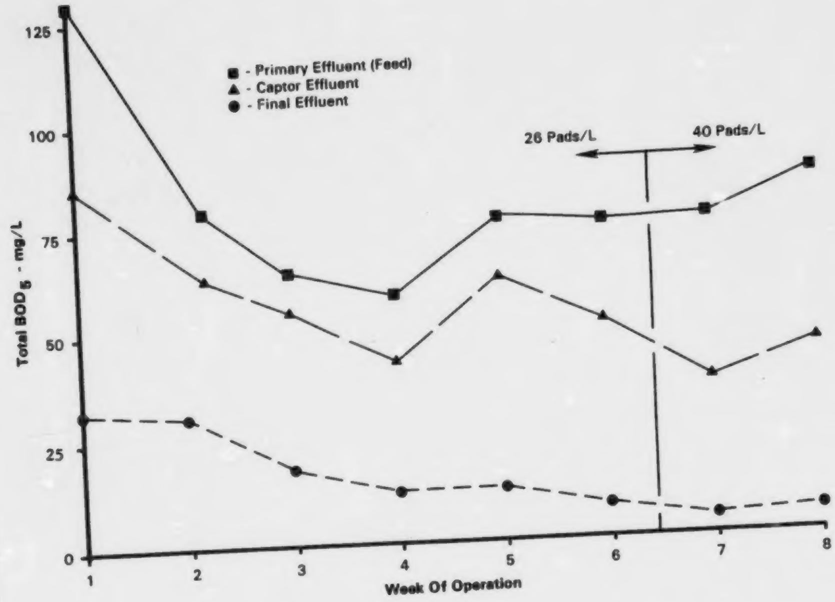

Figure 10. Marion, Illinois pilot plant results Total BOD, 7-day averages.

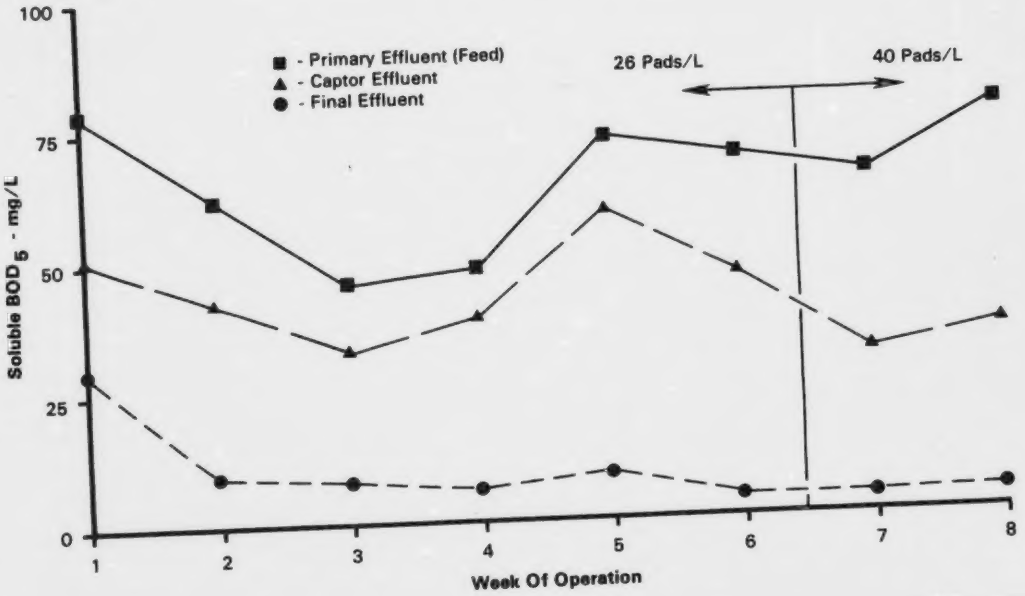

Figure 11. Marion, Illinois pilot plant results Soluble BOD, 7-day averages.

TABLE 5. PERFORMANCE OF THE MARION, ILLINOIS, PILOT PLANT WITH A PAD CONCENTRATION OF 40/L (16 DAYS)

Effluent	Average percent removals			
	Tot. BOD	Soluble BOD	SS	NH_3N
Captor	49	54	-36	29
Final	94	94	92	100

suspended solids and zero ammonia. Unfortunately, there is no reliable control available to compare these data against, as the full-scale plant was suffering severe mechanical problems with the RBC installation during this period.

The pad cleaner was operated for one hour per day during this part of the study, providing an (approximate) pad cleaning rate of 20 to 25 percent per day.

Downingtown, Pennsylvania--

A Captor pilot plant was installed and tested at the Downingtown Regional Water Pollution Control Center to see whether the Captor process could be used to economically upgrade the existing activated sludge plant. This plant has had a history of filamentous bulking, washout of MLSS during high rainfall events, periodic excursions in the effluent BOD (presumed due to industrial toxic discharges*), and inability to achieve consistent nitrification. The original pilot plant was 9.76 m (32 ft) in length with a cross-section 2.44 m by 2.44 m (8 ft x 8 ft). During start-up, problems were observed with pad distribution along the length of the tank. By consensus it was decided to reduce the aspect ratio from 4:1 to 3:1 by blocking off the first 2.44 m (8 ft) of tank length, leaving an effective length of 7.32 m (24 ft). It is generally agreed that the pad distribution improved slightly upon making this modification, although no clear understanding of the relationship between aspect ratio and pad distribution seems to exist at present.

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*Operating personnel are convinced that toxic material was being dumped at night, probably directly into manholes. When they let it be known that they were out to catch the dumper, the problem stopped immediately.

The aeration system originally installed consisted of 72 ceramic dome diffusers installed in four lines down one side of the tank to produce a spiral roll pattern. This arrangement was subsequently modified by removing the line nearest the tank centerline, leaving 54 diffusers. This produced a more effective mixing pattern.

Other characteristics of the pilot plant of interest were as follows:

1. The feed was primary clarifier effluent at a constant flow of 12.6 L/sec (200 gpm).

2. Maximum aeration capacity was 118 L/sec(250 cfm), but was generally held between 38 to 82 L/sec(80 to 175 cfm) using a bleed-off valve.

3. The pad cleaner was located at the effluent end of the tank and discharged cleaned pads to the feed trough, which carried them to the influent end. Pad cleaning occurred once per day for one hour during much of the four-month (approx.) study. During part of March the pad cleaner was operated for four and later for eight hours per day. Rough counts of the pad cleaning rate produced an average value of 150,000 per hour. This figure would translate into a cleaning rate of about 8-9 percent for one hour per day, 34-35 percent for four hours per day and 69-70 percent for eight hours per day.

4. During the course of the study the wastewater temperature ranged from 10.5°C to 12.5°C.

5. Pad distribution along the length of the tank during the study varied, but generally could be expected to be about 30/L in the first third, 40/L in the second third and 50/L in the final third of the basin. The overall average was 42/L.

6. The pad solids during the study varied between 32 mg/pad and 127 mg/pad, with an average of 71 mg/pad, resulting in an "effective" MLSS of only 2990 mg/L. Microscopic examination and oxygen consumption measurements showed the pad biomass to be quite inactive at the beginning of each week due to very low plant loadings on weekends. Activity increased through the week, reaching a peak by Friday. Exceptions were noted when high rainfall events occurred to dilute the incoming sewage.

7. Effluent suspended solids from the Captor plant averaged 74 mg/L, compared to an average influent suspended solids of 66 mg/L. This loss of solids is obviously a major factor in the poor total BOD removals achieved by this plant. A rather low waste sludge concentration was achieved by the pad cleaners; averaging about 0.95 percent solids with a maximum recorded value of 1.32 percent.*

Weekly** average values of total and soluble BOD into and out of the Captor pilot plant are plotted in Figures 12 and 13. Comparing the data from the Captor section alone to that from Marion, IL, shows a worse performance at Downingtown at about the same F/M loading and strength of feed. The only obvious contributing factor is the lower wastewater temperature at Downingtown. There were, however, other possible reasons for the mediocre performance. The operation was plagued with some purely mechanical problems which tended to erode solids from the pads. In particular it was noted that the combination of placement of the pad retaining screen and aeration system geometry was such that large numbers of pads impinged heavily upon the screen, resulting in physical abrasion of pad solids and subsequent loss through the screen before they could be picked up by other pads.

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* Recent data obtained with the same pilot plant at Moundsville, WV, after several adjustments to the pad cleaner, have shown that thicker waste sludges can be obtained, even with low pad solids concentrations.

**The "weeks" actually consist of seven consecutive BOD values. They were not always continuous and did not always consist of data from seven consecutive days, especially near the end of the study, when data were taken about every other day.

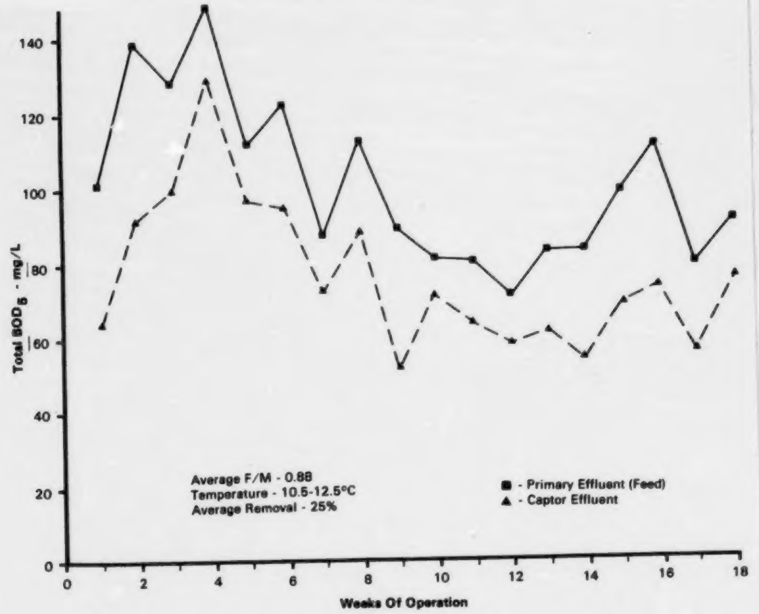

Figure 12. Downingtown, Pennsylvania pilot plant results Total BOD, 7-day averages.

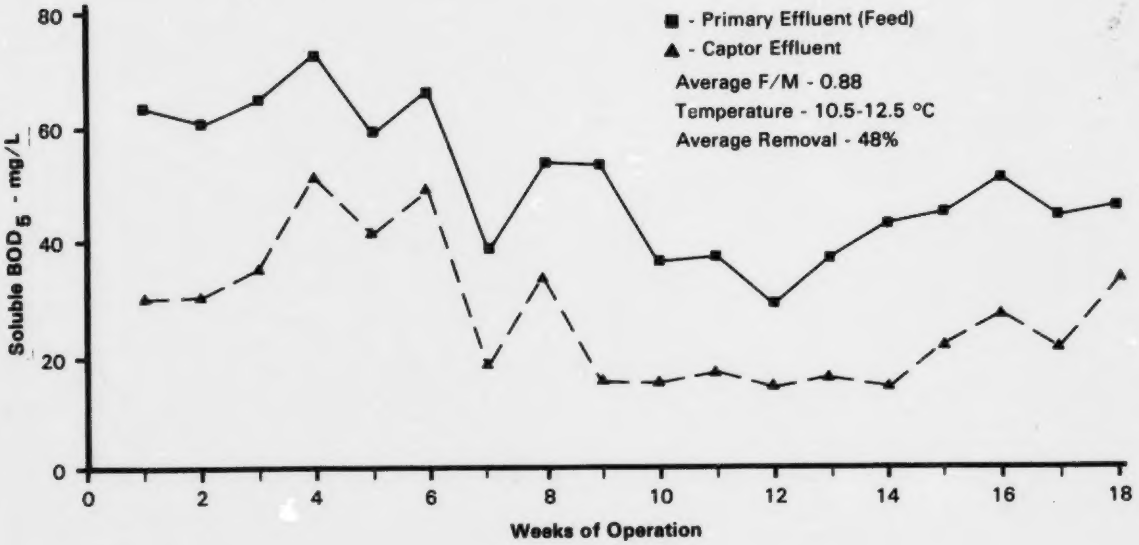

Figure 13. Downingtown, Pennsylvania pilot plant results Soluble BOD, 7-day averages.

Possibly more important, however, it appears that the unique characteristics of the waste loading pattern simply did not allow the establishment of a reasonable steady state with regard to system operating parameters. It is certain that no special steps were taken to attempt to operate the Captor process in response to the varying loading conditions. In fact, to do so would have been presumptuous on the part of the operating staff, as they had no established background of operating experience with Captor to guide them. To take these thoughts a step further, in examining all the development work done to date, there has been so much effort required to solve basic process problems, including hardware improvement, and just getting Captor to "work", that there has been very little time available to the process developers to devote to the fine points of both Captor and overall process optimization. One must realize that the second does not necessarily follow the first when Captor is used as the first stage of a multi-stage biological treatment system.

The downstream process, whatever it is, will probably behave in an optimum way when it receives its "design" load in the absence of substantial pertubations. If an upstream Captor process of finite removal capability, in kilograms of BOD, for example, was always operated to achieve that removal, incoming pertubations would be reduced in amplitude and increased in length, but would still exist. These would be passed on to create stress in the downstream process. If, on the other hand, the Captor process was designed and operated to pass on a more constant load, the overall process result might improve even though the Captor performance was variable and not always at its optimum level. The ability to implement this sort of process operating strategy is an inherent property of Captor, primarily because of the ability to clean pads at rates varying from zero to 100 percent per day (or higher). The wastewater treatment field has not previously had a process whereby the growth rate of the system could be so quickly and conveniently manipulated. In future research and development work on the Captor process, a lot of thought must go into trying to harness this capability.

The application of these somewhat philosophical remarks to Downingtown is straightforward. If Captor had been adopted at Downingtown, it was to have been as a first stage followed by a nitrifying activated sludge system. In the absence of other complications such as high infiltration/inflow or toxic materials entering the system, the BOD loading occurred as a fairly predictable weekly cyclic pattern. Because of the lack of industrial activity (particularly a large commercial bakery) on weekends, the BOD loads to the plant were quite low through Friday night, Saturday, Sunday and into mid-morning on Monday. During these periods loads were received at a rate of 500 to 2000 kg BOD/d (1,100 to 4,400 lb/d). During the remainder of the week loads were more typically 2,900 to 5,000 kg BOD/d (6,400 to 11,000 lb/d). How should the overall system be optimized? We do not have the kind of data base yet which allows us to answer this precisely. However, the following scenario seems intuitively satisfactory.

1. During the low load periods, clean pads at a high frequency and waste sludge to the downstream activated sludge system.

2. As the load increases, decrease the rate of pad cleaning to allow pad biomass to accumulate to near its highest steady-state level. Gradually switch the point of sludge wasting from the downstream process to out of the system.

3. When the desired pad solids level is attained, increase the rate of pad cleaning while continuing to waste solids entirely out of the system.

Employing an operating strategy of this type, it should be possible to keep a fairly steady load on the downstream nitrification system, maintain maximum activity in the nitrification system, equalize aeration requirements and equalize solids loadings from the nitrifying activated sludge tanks to their secondary clarifiers. All these factors should result in improved overall plant performance, but at the expense of performance rating for the Captor portion of the process.

Industrial System--

This system was designed for a low flow (2.6 L/sec [42 gpm]) of strong industral wastewater from the manufacture of plastic specialty products. The chemical oxygen demand (COD) of the wastewater ranges from 1,000 to 2,500 mg/L after chemical pre-treatment, settling and flow equalization. The major characteristics of the Captor system are summarized in Table 6.

TABLE 6. CHARACTERISTICS OF INDUSTRIAL CAPTOR TREATMENT SYSTEM

Reactor (circular)	
Diameter	4.1 m (13.5 ft)
Water depth	4.6 m (15 ft)
Hydraulic detention time	10.7 h
Average flow	1.6 L/sec (25 gpm)
Blower capacity	89.6 L/sec (190 cfm)
Normal aeration rate to control D.O. @ 2 mg/L	40 to 71 L/sec (85 to 150 cfm)
Pad concentration - from 8 Feb. 1984	40 per liter

The system is equipped with a final clarifier because of the amount of growth anticipated during the treatment of such a high-strength wastewater. During system start-up, changes were made to the piping to allow the recycle of settled biological sludge back to the Captor reactor. During the period for which most of the analytical data are available, sludge was being recycled and pad mixing conditions within the reactor were quite poor, with large quantities of pads collected together at the surface in "rafts." Especially bad episodes of pad flotation seemed to correspond to high reactor temperatures, especially those in excess of 32°C (90°F). However, the problem has been somewhat chronic and is believed to be associated primarily with the design of the aeration system. The original design consisted of 12 radial laterals emanating from a centrally located drop pipe, each lateral at 30° from its neighboring laterals. Each lateral had three coarse bubble diffusers spaced at equal distances along its length. This pattern did not provide for the discrete up-and-down fluid movement which experience has now shown is necessary for adequate pad mixing. An attempt to create a "roll" in the reactor by blinding off five adjacent laterals did not succeed in solving this problem; therefore, the decision was made to completely redesign the aeration system. In early September, the aeration system was completely overhauled. Twelve large porous plastic plate diffusers, each equipped with a control valve, were installed around the aeration tank perimeter. At an air flow rate of 51 L/sec (108 cfm) and a pad concentration of 38/L, the pad circulation appears to be excellent and the floating pad rafts are gone.

Most of the performance data for the system is in terms of COD values. BOD/COD correlations have been developed for the influent and effluent and are checked often enough for consistency that they can be used with reasonable confidence to estimate performance relative to BOD removal. These BOD/COD ratios are 0.36 for the feed and 0.14 for the effluent. For most of the performance history available on this system, the pad solids averaged about 100 mg/pad and the MLSS averaged about 2,400 mg/L. At 40 pads/L, this would translate to an EMLSS of 5,680 mg/L except that there was limited contact between the pad biomass and the wastewater. Most of the treatment, except on occasions which are not well documented, was being accomplished by the suspended biomass. A substantial level of treatment even under these conditions was being achieved, but it is clear from an inspection of Figure 14 that once the pad mixing problem at this plant is overcome, a very high level of performance may be expected. Beyond that, little can be said about this system as an example of Captor experience.

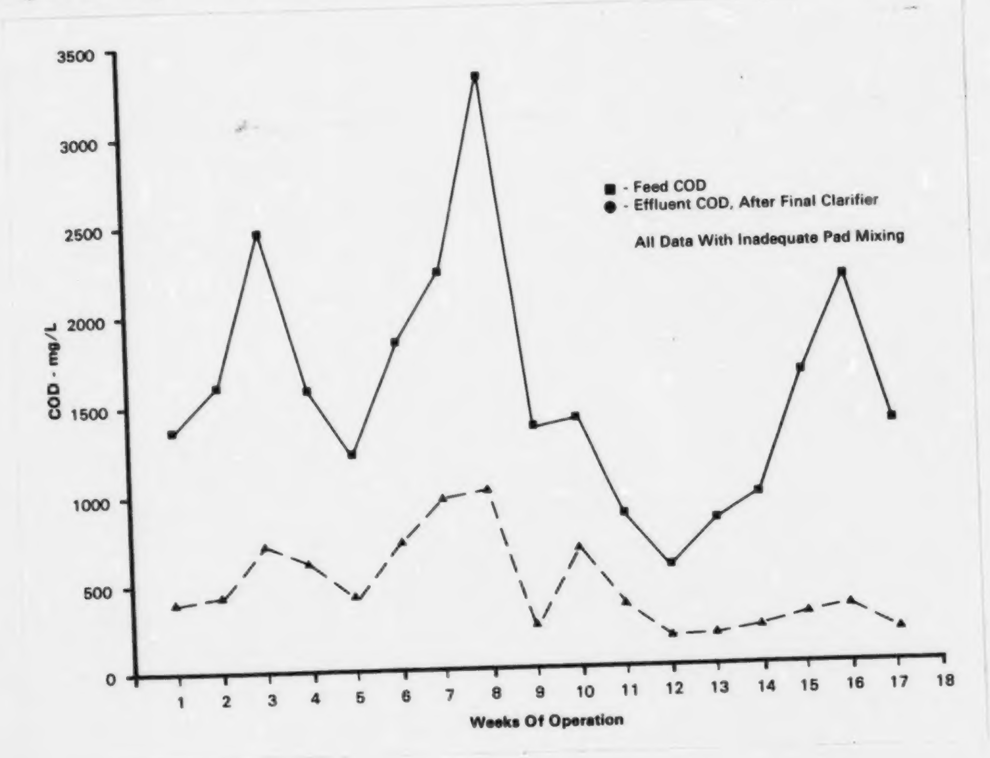

Figure 14. Performance of industrial Captor system.

Experience in the United Kingdom

There is a much longer history of Captor experience in the U.K., most (but not all) of which has been subject to far better controls than in the U.S. Some of the work has been at rather small scale, and this work will be referred to in Section 4 of this assessment. In the present section, only two systems will be reviewed.

Pretreatment of Bakery Wastewater--

The first system designed from the earlier bench- and pilot-scale work was an industrial pretreatment system installed at a commercial bakery. The flow diagram is shown in Figure 15. Discharge of the effluent is to a municipal sewer.

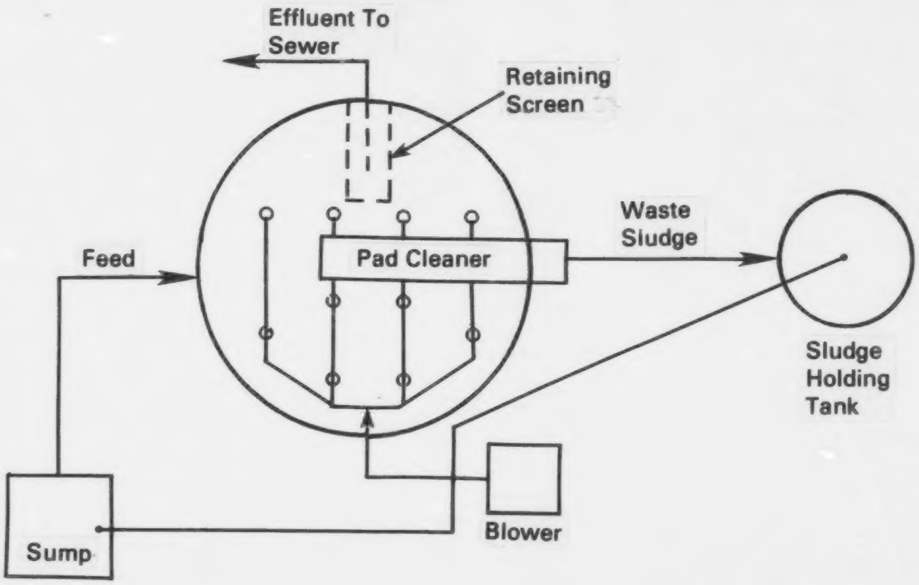
Effluent To Sewer
Retaining Screen
Waste Sludge
Feed
Pad Cleaner
Sludge Holding Tank
Blower
Sump

Figure 15. Captor system for bakery wastewater pre-treatment.

The circular reactor has a volume of only 12.5 m^3 (440 ft^3). Performance standards for this plant are $\leq$ 550 mg/L for COD and $\leq$ 225 mg/L for BOD. As with many small industries, a lot of time and attention has not been lavished on this facility, including the monitoring function. However, a reasonable amount of reliable analyses were obtained during and just after system break-in. The data obtained after achieving a steady-state condition are summarized in Table 7 (4).

Unfortunately, there are no complete records on the day-to-day operation of this facility. Thus, critical questions as to pad biomass concentration, pad cleaning rates, waste sludge production, oxygen utilization, and especially costs of operation cannot be answered. In this regard it is perhaps inappropriate to include this example in the present document. However, on balance the example does provide some additional background data on the process and the reader can judge how effective this performance is relative to available alternatives for comparable degrees of pretreatment.

TABLE 7. CAPTOR PRETREATMENT SYSTEM FOR A BAKERY - POST BREAK-IN PERFORMANCE

	COD mg/L		BOD mg/L		SS mg/L		pH	
	Feed	Final	Feed	Final	Feed	Final	Feed	Final
Maximum	3540	1000	2025	510	926	918	6.8	7.0
Mininum	600	336	350	101	340	440	4.2	6.0
Average	2084	554	1246	255	720	653	5.2	6.7
Average % Removal		74		80				

Average volumetric load 4.3 kg BOD/m^3-d (270 lb BOD/1000 ft^3-d)
Average hydraulic retention time 6.9 hrs.
BOD and COD values based on unsettled samples.

Freehold Water Reclamation Works--

The Freehold plant, located near Stourbridge, West Midlands, was an activated sludge system which needed upgrading to achieve year-round nitrification. The plant consisted of five lanes of basins aerated by a fine bubble diffuser system. To provide the proper controls for the study, one basin was removed from service and the flow was equally divided among the other four basins. Two of these were kept as activated sludge basins and two were converted to two-stage units with Captor in the first quarter and activated sludge in the final three-quarters. The two systems discharged to two separate clarifiers so that effluent comparisons between the Captor-activated sludge and conventional activated sludge systems are possible. The basic flow schematic following the conversion of two lanes is shown in Figure 16.

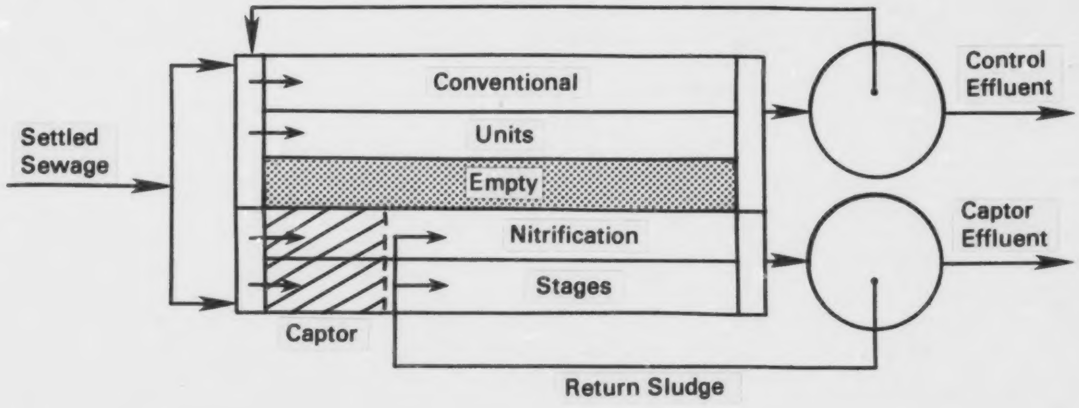
Settled
Sewage
Conventional
Units
Empty
Nitrification
Stages
Captor
Control
Effluent
Captor
Effluent
Return Sludge

Figure 16. Flow schematic to evaluate Captor vs. activated sludge at Freehold.

The Freehold study, begun in September of 1982 and originally planned for two years' duration, represents the most comprehensive investigation of the Captor process as the initial stage of a multi-stage biological system ever attempted. The study was designed for both development and evaluation. Before presenting and discussing the data accumulated thus far on this system, it seems appropriate to deal with some preliminaries which assist in putting the design of the conversion and the data into a proper perspective. The basic design data are presented first in Tables 8, 9, and 10.

TABLE 8. DESIGN LOADING CONDITIONS FREEHOLD WATER RECLAMATION WORKS

	Flow, m^3/d	BOD_5	Load, kg/lane-d
Avg. annual	18,700	144	673
Avg. winter	20,000	148	740
Avg. February	20,000	174	870
Max. day	--	--	1261

TABLE 9. DESIGN DETAILS

Basin geometry 61 m x 3.6 m x 3.0 m SWD
Total volume/basin 659 m^3
First 25% (15.5 m) converted to Captor
Captor volume 165 m^3
Activated sludge volume 494 m^3
Captor support concentration 40,000/m^3
Predicted biomass/pad 200 mg
Predicted MLSS in activated sludge section 3,200 mg/L

TABLE 10. PREDICTED LOADINGS AND PERFORMANCE OF CAPTOR/ACTIVATED SLUDGE SYSTEM - FREEHOLD WATER RECLAMATION WORKS

Period	Captor BOD load		Predicted BOD* removal in Captor, %	Act'd sludge load kg/kd-d	Predicted NH_3-N in final eff., mg/L
	kg/m^3-d	kg/kg-d			
Winter	4.5	0.56	70	0.14	10
Summer	3.5	0.44	80	0.073	1
Annual	4.0	0.50	75	0.08	5

*See comments on the design equation which follows.

First, some comments on the physical facilities and conversion design. The choice of Freehold appears to have been a good one, even though screw pumps had to be added after the primary clarifiers in order to guarantee equal flow distribution to the two comparative systems. The plant was not able to produce consistent nitrification under existing loading conditions, but with the addition of some additional carbonaceous BOD removal at the front end, could be expected to show a dramatic improvement in nitrification. The ability to keep the sludges from the two sides separate was an absolute necessity for a successful study and, although difficult, this was accomplished. Given the unique demands of the study, one aspect of the plant which did not receive adequate attention was the primary treatment. Throughout the course of the study, the special hardware required to make Captor function--pad cleaners and retainer screens--were plagued by plastics, especially plastic strips, which were a continual problem. The plastic materials were never noted as a problem before the conversion, as they did not interfere with aeration basin operation under an activated sludge mode. Several attempts were made to exclude these materials using fine screens in the feed channels, but the screens clogged too rapidly and created a continual maintenance problem. Work to solve this problem continues.

It is possible, even probable, that the problems with oil and plastics at Freehold, although not unique to that plant, are intensified by the design and operation of their particular primary clarifier system. First, the inlet condition seemed to encourage, rather than discourage, short-circuiting. Next, the sludge and scum scrapers were operated intermittently and at perhaps too low a frequency (they did not operate during the three-hour period of our visit). Last, and probably most important, there is no scum baffle downstream of the rotating scum pipe. Thus, it is very easy for floating material to ride underneath the scum pipe and there is nothing to stop the material from exiting the basin once it does pass this point.

Turning to Table 10, the loadings and performance predicted for the Captor-activated sludge side of the plant, there is little doubt that the BOD removals predicted for the Captor section are overly optimistic. The BOD removal correlation developed by Simon-Hartley, Ltd. from previous pilot-scale work was

$$\text{Percent removal} = 100 \exp\left(-.67 \frac{F}{M}\right)$$

and has appeared in several of their internal publications (4,10). However, in the development of this correlation, the effluent BOD values used were based upon the BOD remaining after a one-hour period of settling (11) and are thus not indicative of Captor operation as the first stage of a multi-stage process. Without benefit of an intermediate clarifier, the correlation overestimates the BOD removal by a variable, but unknown, amount. Unfortunately, no corrections were made to the removals calculated for the Freehold conversion to correct for the suspended solids carried into the activated sludge section of the aeration basin from Captor. Thus the actual loadings to this section would be higher than those predicted in Table 10. This error is partially compensated for by the fact that a part of the BOD load to the activated sludge is respiring biomass; that is, some of the feed, F, is also biomass, M. This presents an interesting problem in the proper interpretation of F/M in a multi-stage process, a problem which does not seem to have been addressed before in the literature. It does seem clear that F/M does not have the same meaning here as it does for a process where there is only a small inoculum contained in "F." Thus F/M should probably not be the basis of performance calculations for the second stage of treatment when Captor is used as a first stage. Nor does sludge age appear to offer an easy way out of this dilemma, primarily because part of the sludge inventory has a low probability of being removed from the pads during cleaning because of its location deep inside the pads. If this material deep within the pads is the most mineralized biomass and low in activity so that the part that gets routinely wasted is of a younger physiological age, calculation of a true sludge age would be difficult. Without some research directed towards defining these differences, there is no obvious way of distinguishing "old" from "young" biomass and the concept of sludge age suffers consequently. If highly effective pad cleaners become the norm, the above point becomes less important.

The available data base from the Freehold investigation covers the period from early November, 1983 until March, 1985. Because of the purely mechanical problems previously referred to, the Captor sections in both converted lanes did not have their design complement of pads installed until March, 1985. The first lane (C1) has operated at 28 pads per liter while the second (C2) has operated with only 16/L. At present, both lanes have pad concentrations of 40 per liter, with good pad mixing conditions being experienced. Progress reports summarizing the raw data and the operating log have been written by the Joint Project Manager. These reports have covered periods of from one to three months. The data obtained are extensive and quality control of the analytical techniques is believed to be excellent. Along with BOD and suspended solids data for all key points in the system(s), there are extensive data on sewage flow, air flow, and pad biomass, and limited data on pad cleaning rates and specific respiration rates for both pad biomass and suspended biomass.

Looking first at the overall aspects of the study, Figures 17 and 18 provide comparisons of the monthly average final effluent BOD and suspended solids for the side-by-side systems.

The differences during the first six months are dramatic, especially considering all the mechanical problems detailed in the progress reports as the pad cleaners went through several stages of development and the investigators learned about balancing the mixing and aeration. The differences begin to disappear through the next three months as the effluents for both systems are seen to continually improve. Because the first indications of nitrification in the Captor-activated sludge system are observed in mid-July, the increasing

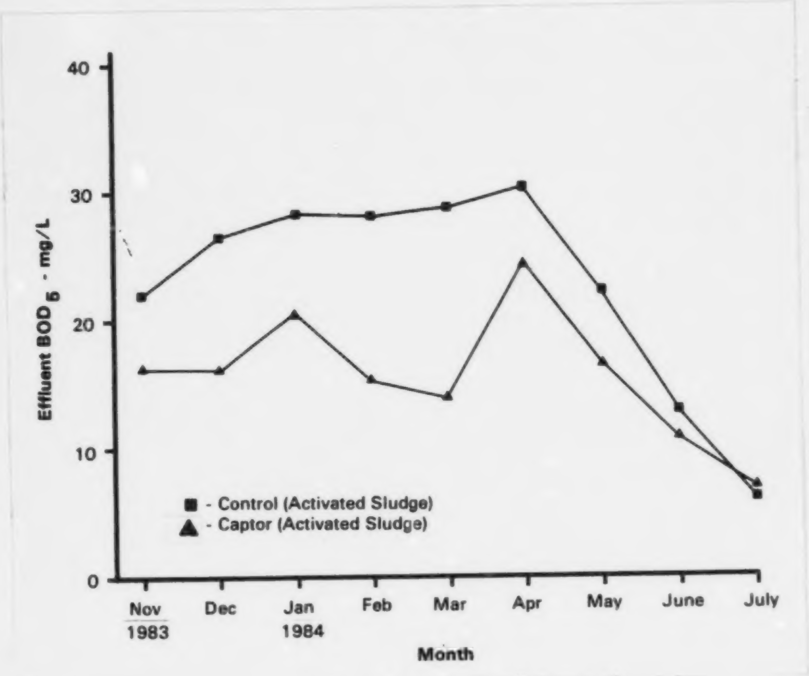

Figure 17. Freehold wr plant - monthly average effluent BOD.

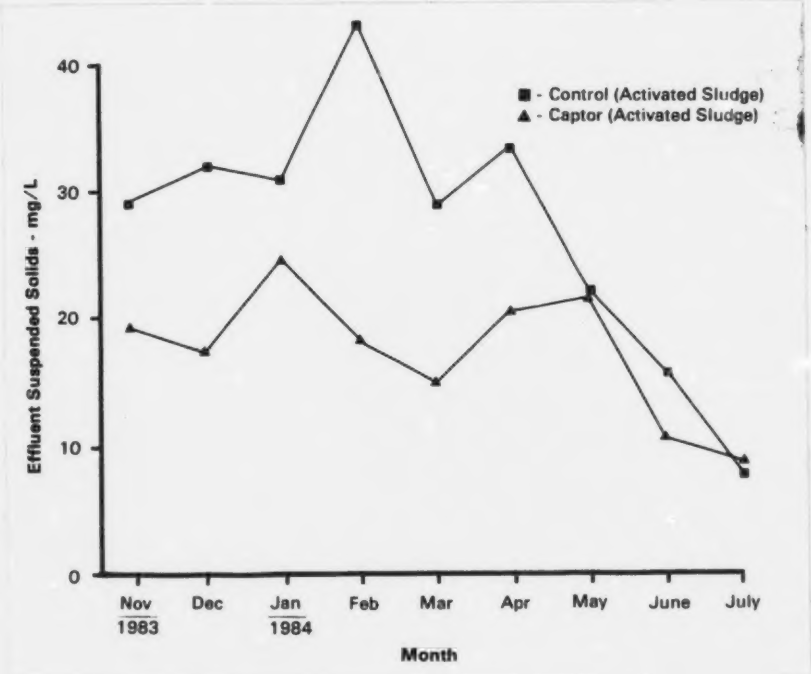

Figure 18. Freehold wr plant - monthly average effluent suspended solids.

wastewater temperature is likely the primary cause for the improvement noted in both systems; activated sludge benefiting equally with the multi-stage system. As for the significant differences noted from November through April, there are several possible explanations. One relates strictly to the differences in the settling characteristics of the solids produced during the colder periods of operation. Data from the Linpor work (see Section 5) and also from a recent survey of coupled trickling filter-activated sludge processes (12, 13) lend support to this idea. Unfortunately, there are no SVI or other settling rate data which can be used to test this possibility. Another theory is that the Captor process is simply more robust than activated sludge at lower temperatures. This possibility cannot be tested either, since frequent respiration rate measurements are only available for February, 1983.

In June of 1984, under the flow and loading conditions shown in Figure 19 (loading based upon filtered BOD values), a 24-hour survey of the two Freehold Captor sections was carried out by the project development team (14). The raw data from this survey are given in Table 11. One pad cleaner in each lane was run for the first five hours of this test and approximately 180,000 pads from each lane were cleaned.

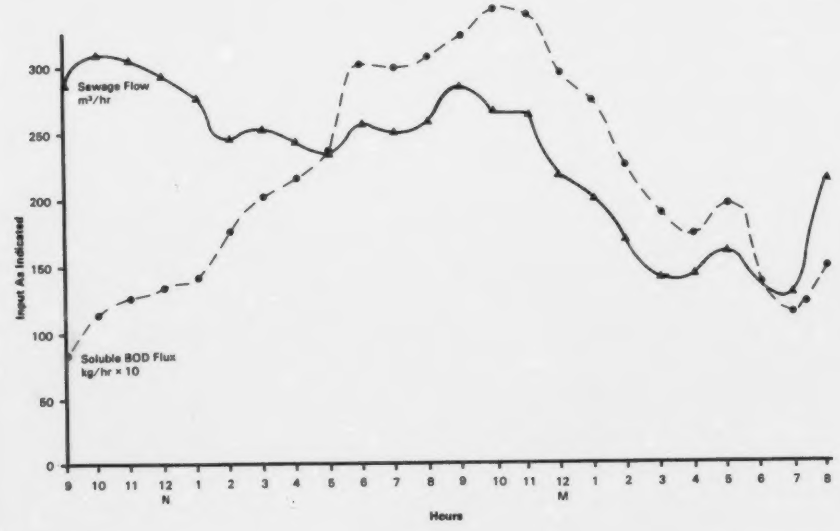

Figure 19. Flow and soluble BOD load during 24-hour survey.

TABLE 11. FREEHOLD 24-HOUR SURVEY, JUNE 1984 (ALL BOD DATA BASED ON FILTERED SAMPLES)

Time	Sewage flow m^3/hr	Air flow m^3/hr	BOD_5 feed mg/L	Values C1 Eff mg/L	Values C2 Eff mg/L	D.O. C1 mg/L	D.O. C2 mg/L	Biomass/pad C1 mg	Biomass/pad C2 mg	Respir. rate mg O_2/g-hr C1	Respir. rate mg O_2/g-hr C2	Spec. rem. rate mg BOD/g-hr C1	Spec. rem. rate mg BOD/g-hr C2
9	276	1329	30	20	20	4.7	4.5	129	197	--	54.5	7.5	7.3
10	312	1303	36	27	27	5.0	4.7	86	178	85.0	--	10.8	8.2
11	306	1342	41	30	28	5.0	5.0	112	188	--	56.9	11.6	11.1
12	282	1347	47	33	31	4.2	4.6	162	186	49.2	--	7.3	12.0
13	253	1095	56	40	37	3.2	3.0	167	205	--	63.8	8.3	11.8
14	247	1041	71	48	44	3.0	2.8	160	204	57.5	--	11.6	20.0
15	253	1187	80	52	47	3.7	3.6	200	234	--	63.1	11.7	17.0
16	243	1365	90	56	51	3.6	2.6	167	193	55.1	--	16.3	25.8
17	234	1360	103	59	58	2.8	4.9	175	218	--	68.0	18.4	24.0
18	256	1355	118	63	68	3.7	2.5	175	189	52.3	--	29.9	34.1
19	251	1563	119	66	65	4.5	4.4	180	198	--	78.4	24.7	39.2
20	256	1870	120	69	64	4.5	4.4	171	227	56.5	--	26.7	34.5
21	283	1850	113	65	60	4.6	4.5	174	230	--	73.9	27.6	32.5
22	263	1848	139	92	82	4.4	4.5	173	220	50.7	--	25.1	33.7
23	261	1636	137	101	100	3.8	3.5	175	252	--	72.9	20.0	18.3
24	217	1320	134	101	96	1.6	1.5	166	218	50.3	--	19.8	20.0
1	199	1304	137	100	101	2.0	2.6	168	239	--	61.5	12.7	14.2
2	166	1304	135	102	89	2.3	2.5	200	227	46.7	--	9.8	19.3
3	138	1315	136	99	81	1.7	2.2	185	239	--	59.2	9.6	16.7
4	140	1306	122	87	75	1.4	1.8	156	233	46.0	--	10.0	16.4
5	160	1290	122	86	80	1.4	1.7	142	227	--	65.4	13.8	17.7
6	134	1295	102	76	70	1.4	1.7	148	214	5.0.7	--	7.8	12.3
7	125	1291	88	68	62	1.4	2.1	177	208	--	68.1	4.2	9.1
8	214	1289	68	62	56	1.0	2.0	178	219	41.8	--	2.8	7.4
Min.	125	1041	30	20	20	1.0	1.5	86	178	41.8	54.5	2.8	7.3
Max.	312	1870	139	102	101	5.0	5.0	200	252	85.0	78.4	29.9	39.2
Avg.	227	1383	98	67	62	3.1	3.3	163	214	53.5	65.5	14.5	19.3

Using the data produced during the 24-hour survey, several standard statistical tests were run to compare the two Captor lanes. In all cases, this involved testing the null hypothesis that the means of measured and calculated parameters over the 24-hour period were equal at the 0.05 level of significance. Table 12 summarizes the results of the hypothesis tests.

First, the effluent from C1 is virtually identical to that of C2 although C1 contains many more pads than C2, and in fact has a higher EMLSS concentration. However, the biomass in C2 shows a higher respiration rate and a higher specific BOD removal rate, and the products of these parameters and the EMLSS concentration are not significantly different when comparing the two lanes. As would be expected, the aeration tank dissolved oxygen levels are not significantly different either, as long as there is roughly equal distribution of air to both lanes. These tests indicate that the activity of the pad biomass is at least as important as the pad concentration (number/L) and the pad biomass level (mg/pad). The Simon-Hartley, Ltd. analysis of these data speculated that a dissolved oxygen limitation may exist at Freehold, critical levels being below 4 mg/L. This seems a distinct possibility. In addition, there is not much question that the substrate supply rate (input BOD flux) may also limit growth and activity in this system.

TABLE 12. STATISTICAL COMPARISONS - FREEHOLD CAPTOR LANES 1 AND 2, 24-HOUR SURVEY, JUNE 1984 (BOD DATA FROM FILTERED SAMPLES)

Parameter	Captor Lane 1		Captor Lane 2		Results of testing difference of means at 0.05 signif. level (n) = no. of samples
	Mean	St'd dev.	Mean	St'd dev.	
Eff. BOD, mg/L	66.5	25.5	62.0	23.5	No. diff. (24)
Susp. pads/L*	17.9	1.6	11.4	1.0	Signif. diff. (24)
Biomass/pad, mg	163	25.6	214	19.7	Signif. diff. (24)
Equiv. MLSS, mg/L	2919	517	2446	333.5	Signif. diff. (24)
Mid-tank D.O. mg/L	3.12	1.36	3.26	1.18	No. diff. (24)
Biomass resp. rate, R mgO_2/g-hr	53.5	10.9	65.6	7.2	Signif. diff. (12)
Specif. BOD rem. rate, K mg BOD/g-hr	14.5	7.8	19.3	9.5	Signif. diff. (24)
EMLSS x R, mg/L-hr	153.2	20.1	160.6	27.6	No. diff. (12)
EMLSS x K, mg/L-hr	43.1	25.5	47.3	23.3	No. diff. (24)

---

*The measured means represent 63% (C1) and 69% (C2) of the actual numbers of pads placed in these lanes. The unaccounted-for pads are collected in floating rafts. Each of the 24 samples consisted of sub-samples from 14 separate locations.

SECTION 6

TECHNOLOGY ASSESSMENT

PROCESS THEORY

Traditionally, wastewater has been biologically treated at relatively low volumetric rates of reaction in large tanks requiring high separation costs and high power consumption for mixing and aeration. A strategy to alleviate this situation has been referred to as process intensification (1). Briefly, process intensification seeks to:

- increase volumetric rates of reaction,
- reduce reactor size,
- improve separation processes,
- enhance operational control capability, and
- enhance design capabilities.

Both biological flocs and films provide certain properties which could be engineered to achieve at least some of these goals. Atkinson et al. (2) have concluded that this engineering would be best facilitated, however, by the ability to produce biomass of any size, shape and density using any substrate-microbe system. This can be be achieved by immobilization of the biomass in some form.

It has long been established that the mixed microbial cultures in wastewater treatment have excellent adhesion characteristics and readily form layers of immobilized biomass on stone, glass, plastic and other commonly available materials. These immobilized systems have the advantage of producing high biomass concentrations which are largely independent of flow-through and do not suffer from washout. In simplest form, these processes include trickling filters and the rotating biological contactor. Although greatly improved upon in the past decade, these fixed-film systems suffer the disadvantages of unpredictable biomass hold-up and variability in local hold-up, which inevitably lead to variable performance and uncertain design capability.

A more recent development, the fluidized bed employing immobilized biomass, may be designed to overcome some of these difficulties. In a completely stirred reactor containing uniform, suspended, immobilized biomass particles, biomass hold-up may be controlled by attrition which results from particle/particle and particle/wall contacts. Steady biomass hold-up may thereby be achievable through proper hydraulic design. Conversely, the fluidized bed could be designed to provide suspended particles of different sizes, shapes or densities so as to control attrition within the reactor and enhance recovery of attached biomass from the system with minimal disturbance (2).

In an effort to develop a system of biomass particles of controlled size, shape and density, Atkinson (2) believed that the system should allow all of the natural mechanisms of adhesion and flocculation to take place in a low-shear environment. Control of the particle size would then be achieved through either physical or fluid mechanical means. Early work in this direction with the fungi, Aspergillus foetidus, was initially performed at the University of Manchester (U.K.) (UMIST) by Perez (3) who used layers of stainless steel mesh wound about a stainless steel draft tube in an air lift fermenter. Later this work was extended to suspended particles of stainless steel mesh by Atkinson and Lewis (4). Since that work in 1977-1978, support particle size, shape and material has markedly changed and the concept has been extended to encompass a wide range of biochemical reactions employing both pure and mixed cultures.

PBS particles can be placed in fixed, expanded or fluidized beds or in agitated tanks. In each system, the control of biomass hold-up, recovery of biomass, performance and design will vary. Table 13 summarizes some of these characteristics of PBS reactors (5).

TABLE 13. CHARACTERISTICS OF REACTORS CONTAINING PBS PARTICLES (5)

	Fixed/expanded beds	Fluidized beds/agitated beds	
	Variable particle biomass hold-up	Variable particle biomass hold-up	Steady particle biomass hold-up
Biomass control	Back-washing	Continuous particle removal and cleaning (particles could be removed periodically	Particle/particle/wall attrition within fluidized beds; particle/particle/agitator attrition
Biomass recovery	Washings collected in a humus tank	At high concentration external to reactor	Conventional clarifier
Reactor performance efficiency, e.g., carbon removal	Variable	Steady (variable for periodic particle removal)	Steady
Design	Requires prediction of the variation of the bed biomass hold-up with time	Requires prediction of the variation of the bed/particle biomass hold-up with time	Facilitated by the fact that all aspects of performance are steady and both particle and bed biomass hold-ups preselected

The new field of PBS particle technology is still in its early stages of development and the biochemical, chemical and physical theories dealing with systems mechanisms are still being formulated. A brief theoretical synopsis of the current state-of-the-art follows.

Porous Support Particles

Biomass support particles, interwoven three-dimensional webs providing a random latticework, have evolved from hand-wound stainless steel spheres to the present polyurethane foams. It is not certain from a review of the published literature when the first work with porous biomass support particles (PBSP) was introduced or what those materials might have been. The important physical characteristics of these particles include high porosity and an open structure. The particles have been prepared from a variety of materials with specific gravities both greater and less than that of water, and in a range of sizes and shapes.

PBSP are necessarily open enough to allow normal biological flocculation mechanisms to take place in a low-shear environment and, subsequently, to entrap small flocs within the lattice structure. Biomass stability is thought to be aided by adhesion between organisms and the particle surfaces within the particle, the winding of filamentous organisms about the elements of the lattice, and the entrapment of flocculent biomass structures (2).

Since biomass completely permeates the lattice structure, particle size and shape as well as porosity will dictate diffusional control on the entrapped biomass. Finally, the physical properties of the PBSP will influence the fluidization, hydraulic distribution, wear and handling characteristics of the PBSS. For example, spherical particles are easily fluidized and are well characterized with respect to their fluidization properties and diffusional limitations. In contrast, cuboids have a large dimension which aids in handling and a smaller dimension which may be independently adjusted for diffusion limitation, but fluidization properties are not well defined and hydraulic distribution can be a problem. Since pad costs represent a significant portion of PBSS costs, pad wear is of great concern. Particle/particle and particle/wall contacts as well as pad handling mechanisms may result in significant wear of pads.

Table 14 summarizes the characteristics of typical biomass support particles (5).

TABLE 14. CHARACTERISTICS OF TYPICAL PBS PARTICLES (5)

Matrix material	Method of preparation	Shape and size	Density (i) of matrix (ii) of biomass filled particle	Porosity of particle
Stainless steel wire	Single strand of wire, weft knitted and compressed in a die	Spheres, 3 to 30 mm diameter	(i) 7.7 g/cm^{-3} (ii) 2.42 g/cm^{-3}	0.80
Polypropylene strands	Single strand of polypropylene, weft knitted and hand rolled into a toroid. Heat sealed.	Overall diameter 53 mm. Torus diameter 20 mm	(i) 0.9 g/cm^{-3} (ii) 1.084 g/cm^{-3}	0.92
Reticulated polyether foams	Expanded foams with lamellae collapsed by sonic shock waves or other methods	Cuboids 10 x 10 x 2 mm to 25 x 25 x 12.5 mm Cubes 12 to 17 mm	(i) 1.2 g/cm^{-3} (ii) 1.103 g/cm^{-3}	0.95-0.97
Matted reticulated polypropylene	Matted in the manner of non-woven fabrics and heat bounded	Cuboids 25 x 25 x 6 mm	(i) 0.9 g/cm^{-3} (ii) 1.09 g/cm^{-3}	0.95

Fluidization and Hydraulic Distribution

The fluidization and hydraulic distribution of PBSP is an important element in successful PBSP operation. The fluidization of stainless steel wire PBSP spheres was studied by Webb et al. (6). They found that the fluidization behavior of filled spherical PBSP was qualitatively similar to that of solid spheres (6 mm diameter) and that the Ergun (7) correlations modified for surface roughness gave satisfactory predictions of minimum fluidizing velocities for these PBSP. Partially filled or empty PBSP required substantial modification of these correlations to allow for fluid flow through the particles.

The fluidization of low-density polypropylene toroids (sp. gr. - 0.91, porosity - 92%) was reported by Walker and Austin (8). A pseudo-fluidization of these particles was achieved by introducing fine bubbles of air below the bed, which was sufficient to cause the bed to expand downwards into the less dense mixture of air and water. Initially, the unfilled particles entrapped air and floated; but once biomass was established in the particle, air entrapment became less of a problem. Air flows required to induce pseudo-fluidity of these particles increased as particle numbers per unit volume increased and as dry weight of biomass per particle decreased. Furthermore, there was an upper limit of particle numbers per unit volume where no amount of air flow could move the bed. An extension of this work to a more porous polypropylene pad (95 to 97%) showed similar fluidization properties, with an important difference. Higher porosities resulted in higher biomass concentrations and concomitant higher particle densities which approached or exceeded that of water. Air flow requirements for fluidization, therefore, were dramatically reduced and more stability of fluidization was noted.

With the introduction of higher-density reticulated foam pads (sp. gr. - 1.1, porosity - 97%), the fluidization and distribution of the pads did not require the higher superficial velocities needed to fluidize the stainless steel PBSP or the high gas flows to induce pseudo-fluidity of the lighter-than-water polypropylene particles. Particle motion was controlled by the intensity of gas flow and particles behaved as elements of the liquid in which they were submerged. The behavior of PBSP in this type of system is difficult to describe and has not yet been sufficiently modeled. Observations by Black et al. (9) pointed out that:

- when gas flow was introduced over the entire bottom area of the reactor, circulation was poor and there was a tendency for particles to float; and

- good liquid/PBSP mixing was most effectively achieved by introducing gas over only a portion of the reactor bottom area.

These observations were further supported by the full-scale experience at Freehold in the U.K. and at an industrial system in the U.S. (Section 5). Based on these experiences, an aeration system was devised to provide for regions of downward liquid flow and effective recirculation by means of proper diffuser distribution (U.K. Patent Application, 1982). Work continues on this important design feature both at the Water Research Centre in the U.K. and at Linde Aktiengesellschaft (AG) in Munich.

Biomass Hold-Up Characteristics

The PBSP provides a site for the development of biomass in flocculent, filamentous and attached forms. It has been demonstrated that these particles can be filled with a wide variety of organisms, including those that do not flocculate, at biomass concentrations up to 100 g (dry weight)/liter (free particle volume) (2,9). Applications of PBSS in a variety of biological reactor systems under aerobic and anaerobic conditions are presented in Table 15 (10).

The actual mechanisms of biomass development and maintenance within PBSP are not well understood. It is clear that the flocs formed within the particles are robust enough to allow a sufficient degree of particle movement without loss until they extend beyond the limit of the particle structure. Control of biomass hold-up may then be affected by a balance between biomass growth and attrition. The open structure of the reticulated foams permits gas evolved by the biomass to escape freely without disruption of the biomass integrity and enhances diffusion of substrate, oxygen and waste products throughout the particle matrix. Although some researchers reported biomass "aging" and mineralization with time in PBSS (8), stable biomass activity appears to be the more prevalent finding for a variety of substrate systems (9,16,17,18).

The overall density, P_{pw}, of a PBSP may be estimated by:

$$P_{pw} = P_m (1 - \emptyset) + P_{ew} \qquad (6.1)$$

TABLE 15. SOME REPORTED APPLICATIONS OF BSPs

Organism	Product	PBS system*	Comment	Reference
Mixed culture (aerobic)	Waste treatment	FOAM/CBF	Up to 160 m^3 retrofit to existing activated sludge plants	Walker & Austin (1981) (8). Richards & Wilson (1983) (11).
Mixed culture (anaerobic)	Methane	FOAM/CBF	1 liter	Fynn & Whitmore (1982) (12).
Yeast	Ethanol	Stainless spheres/FBF	2.0 liter	Black et al. (1984) (9).
		FOAM/CBF		
Acetobacter sp.	Acetic acid	Stainless spheres	Fixed bed	da Fonseca, (1983) (13).
Aspergillus sp.	Citric acid	Stainless spheres/FBF		Atkinson & Lewis (1980) (4).
Trichoderma sp.	Cellulase	Stainless spheres/SBF	Approx. 7 liters	Fukoda et al. (14).
Capsicum sp. (plant cell)	Capsaicin	FOAM	Shake flasks	Lindsey et al. (1983) (see (10)).
Humulus sp.	Hop flavors	FOAM	Shake flasks	Rhodes & Kirsop (1982) (see (10)).
Mixed cultures (aerobic)	Waste treatment	FOAM/CBF	Up to 45 m^3 polishing, improve SVI	Hegemann (1983) (15). Hegemann & Englmann (1983) (16). Reimann (1984) (17).
Mixed cultures (aerobic)	Nitrification of secondary effluent	FOAM/CBF	1 m^3	Reimann (1984) (17).

*CBF - Circulating bed fermenter

FBF - Fluidized bed fermenter

SBF - Spouted bed fermenter

where p_m is the density of the support matrix, P_{ew} is the effective wet biomass concentration based on the total particle volume, V_p, and $\emptyset$ is the particle porosity. If the immobilized biomass is assumed to consist of a water phase (density P_w) and a biomass phase of constant wet density, P_{bw}, then

$$P_{ew} = (P_w (1 - x) + P_{bw} x) \emptyset \qquad (6.2)$$

where x is the fraction of the porosity filled with biomass of density P_{bw}.

Overall particle densities calculated from Equations 6.1 and 6.2 for a variety of PBSP shown in Table 14 are relatively insensitive to the density of the support matrix because of the high PBSP porosities, and the similarities between the density of water and biomass. Thus, a tendency toward particle classification is relatively small for most PBSS.

The dry biomass hold-up, P_e, of the PBSP of high porosity may be estimated by:

$$P_e = m_p/V_p \qquad (6.3)$$

where m_p is the dry weight of biomass in the particle. When particles are completely filed with biomass at a solids concentration, P_b (dry weight per unit wet available volume) corresponding to that of drained wet biomass, then

$$P_e = P_b\emptyset \qquad (6.4)$$

and the amount of biomass (dry) per particle may be estimated for a given PBSP as

$$m_p = P_b \emptyset V_p \qquad (6.5)$$

Finally, the overall concentration contributed by the PBSP to the reactor, P_f, would be calculated as

$$P_f = N_p m_p/V_R \qquad (6.6)$$

where N_p is the total number of particles in the reactor and the reactor volume is V_R. Added to the value calculated by Equation 6.6 is the free biomass suspended in the reactor and that attached to the reactor walls as film. The contributions to the entire reactor system made by the suspended portion of the biomass can be significant, as in the Linpor systems designs.

Recent experiments with 6 mm polyester foam PBSP cubes with a porosity of 97% and varying pore sizes ranging from 30 to 60 pores per inch revealed that biomass hold-up, m_p, for a yeast culture increased with the number of pores per inch (9). Under all conditions, the 60 ppi particles contained more biomass than those at 30 ppi for the same particle size and porosity. Similar unreported studies by Simon Hartley on 25 x 25 x 12.5 mm polyether foams with mixed cultures indicated an optimal pore size of 30 ppi with decreases in biomass hold-up at higher or lower pore sizes. Reasons for these findings are still unclear, but these studies suggest that pore size and pad size are important variables in designing PBSS.

For particles with steady biomass hold-ups, it is reasonable to suggest that m_p represents a balance between overall growth and degree of attrition. Thus, when the overall specific growth rate, G, exceeds the specific rate of attrition, T, the biomass hold-up will increase as:

$$\frac{dm_p}{dt} = (G - T)m_p \qquad (6.7)$$

According to the biological rate equations (19), it can be deduced that as m_p increases G decreases due to the greater diffusional limitation on entering substrate until a balance (steady state) is achieved between growth and attrition at a given reactor substrate concentration. Atkinson et al. (18) have deduced that T, under a given set of conditions of particle and bed hydraulics, will either be a function of m_p or a constant. Thus, for steady state conditions m_p will be either proportional to G or be a constant.

In analysis of data collected on a glucose-mineral salts media, Atkinson et al. (18) indicated that a relationship existed between biomass hold-up and reactor glucose concentration. Assuming that

$$m_p = f(G) \text{ and}$$
$$G = f\left(\frac{C_o}{\beta+C_o}\right) \qquad (6.8\ a)$$

Atkinson showed that

$$m_p = m_p \max \left(\frac{C_o}{\beta+C_o}\right) \qquad (6.8\ b)$$

where C_o is the reactor substrate concentration and β is an constant.

This work also suggested that biomass hold-up increased with increased influent glucose concentration up to some limiting value. Thus, for a given reactor turbulence, there is likely some limiting biomass concentration that can be effectively maintained within a PBS particle under steady-state conditions.

Waste strength alone does not dictate biomass hold-up, as demonstrated in tests conducted in the 25 m^3 pilot plant system at the Water Research Centre. Biomass hold-up measured in this pilot plant with a wastewater BOD of about 200 mg/L ranged from 100 to 120 mg biomass per pad, as compared with hold-ups in excess of 200 mg/pad at the Freehold facility, where wastewater BOD values were about 140 mg/L. It would appear from this preliminary data that wastewater characteristics, organics loading rate and hydraulic regime all contribute to the accumulation of biomass within the PBSP.

Substrate Uptake Relationships

The overall rate of substrate removal, R_f, in PBSS is the result of the combined metabolic effects of the support particles, films and suspended flocs. The latter is the result of biomass erosion from PBSP and reactor walls as well as growth of the suspended biomass within the reactor. The general rate equation may be written:

$$R_f = R_p M_p + NA + R_s M_s \tag{6.9}$$

where R_p and R_s are the overall specific rates of substrate uptake in the reactor by the PBSP and by the suspended flocs, respectively, N is the overall rate of substrate uptake per unit area of microbial film, M_p and M_a are the total quantities of biomass on the support particles and freely suspended flocs, respectively, and A is the area of microbial film. Atkinson et al. (18) have developed rate equations for this system assuming that the intrinsic microbial kinetics are described by the Monod equation and that there is a strong diffusional limitation within the PBSP and the attached reactor films but not within the freely suspended flocs.

In summary, these equations are presented in Table 16 (18). Results of experiments using stainless steel spherical PBSP with glucose as a substrate indicated that the overall rate of glucose uptake by a mixed microbial population followed half-order kinetics in C over a range of substrate concentrations up to 4 g/L. A typical result of these experiments is shown in Figure 20 (18).

Studies currently under way at the Water Research Centre employing a 25 m^3 pilot facility have produced a relationship as depicted in Figure 21. Attempts to develop a simple, useful design relationship for BOD_5 uptake have not yet been entirely successful, since the defining independent variables are not yet well delineated. An important missing element in the relationships presented by Atkinson et al. (18) as well as in Figure 21 is the biomas history (usually characterized by mean cell residence time).

In the CSTR operated by Atkinson et al. (18), "steady-state" biomass was claimed to exist after three days of constant biomass hold-ups and conversion efficiencies. Under steady-state conditions, it is assumed that biomass wasted from the system has the same activity as that in the PBS particles. If this is not the case, steady biomass hold-up would not imply steady mean cell

TABLE 16. BIOLOGICAL RATE EQUATIONS FOR PBSS (20)

$$R_p = \frac{R_{max}}{\alpha k_{2p}\ d_p/b} \left[\frac{2C_{p*}}{K_m}\right]^{1/2} \qquad (6.10a)$$

$$N = \frac{R_{max}\ P_{of}}{k_{2f}} \left[\frac{2C_f{*}}{K_m}\right]^{1/2} \qquad (6.10.b)$$

$$R_s = R_{max}\ \frac{C_s{*}}{K_m + C_s} \qquad (6.10\ c)$$

where $K_{2i} = \left[\frac{P_{bi}\ P_{max}}{K_m\ D_e}\right]^{1/2}$

and

$$\frac{C_i{*}}{K_m} >> 1$$

$C_o = C_{p*} = C_{f*} = C_{s*}$

$C_i{*}$ are substrate concentrations at the interface

K_m is the Monod coefficient

R_{max} is the maximum specific uptake rate

D_e is the diffusion coefficient

α is a shape factor

d_p is the overall diameter of the particles

P_{of} is the density of microbial film

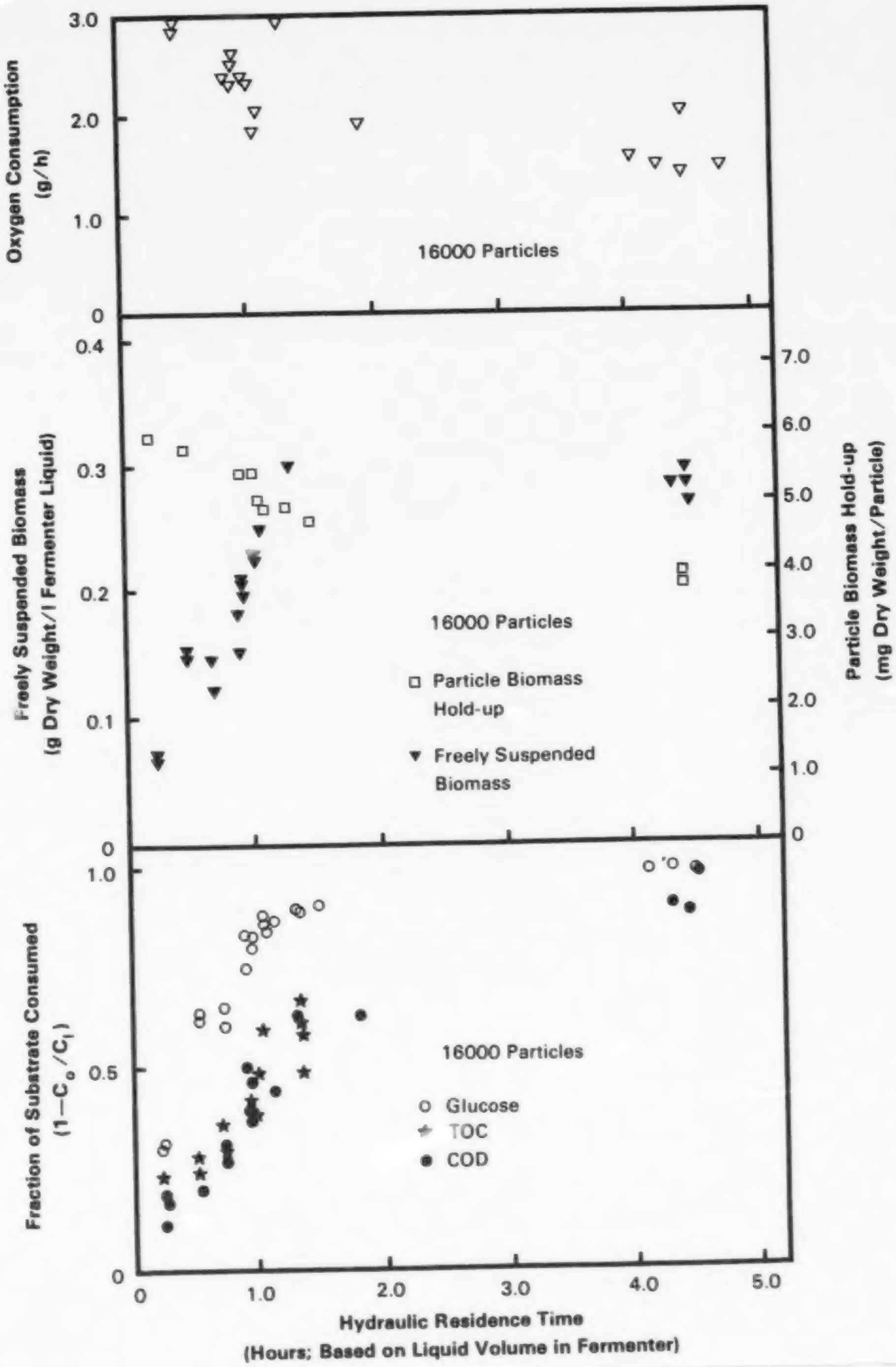

Figure 20. Performance of PBSS using glucose (18).

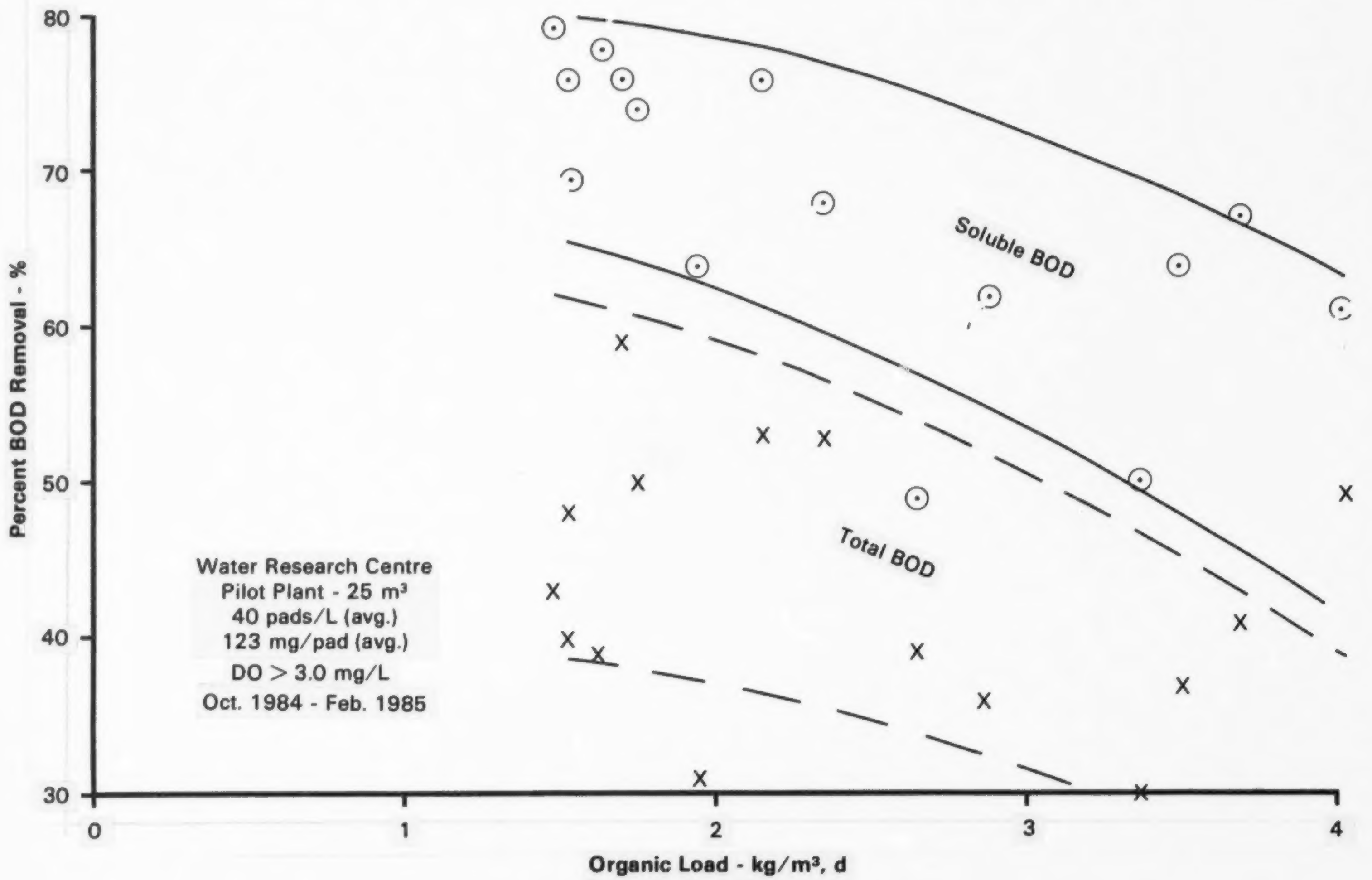

Figure 21. BOD removal relationships - Captor.

residence times. That Atkinson et al. (18) were able to achieve a reasonable degree of reproducibility over a 24-month period of continuous operation suggests that the assumption of steady-state mean cell residence times is probably valid for their system.

A similar question must be raised for systems employing mechanical removal of biomass (Captor). Here, mean cell residence time is purportedly controlled by PBSP squeezing rates. There is some evidence to suggest that as squeezing rate increases, PBSP biomass concentrations decrease, biomass activity increases (as measured by oxygen uptake rate) and more efficient suspended solids "clean-up" occurs. There is a need for additional research on the impacts of PBSP cleaning on biomass activity before useful design models can be developed for these types of systems.

The impact of diffusional limitations on system performance must also be addressed in modeling efforts. The Atkinson et al. (19) biological rate equations account for diffusion through effectiveness factor correlations. These corrections cannot be overlooked, especially in scaling up pilot studies.

An important design parameter used in modeling biological systems is the biomass yield coefficient. There is a paucity of data on biomass yield for PBSS at this time. The reason for this deals primarily with methods of analytical measurement. Yields must account for PBSP biomass, suspended biomass and fixed films along reactor walls (in laboratory-scale systems). Very preliminary data from wastewater treatment facilities indicate biomass yields ranging from 1.2 to 0.3 kg/kg BOD_5 removed, depending upon cleaning rates (20).

One final point should be made relative to substrate uptake modeling. The fundamental work reported by Atkinson et al. (18) was conducted with a pure substrate glucose, and glucose uptake was directly monitored. Attempts to monitor TOC or COD uptake in these studies produced poor correlations, as might be expected, since both measurements are nonspecific. In wastewater systems, these "lumped parameters" of measurement are commonly used. Furthermore, filtered, settled or total samples may be analyzed. These measurement constraints add to the difficulty of effective PBSS performance modeling.

Other Considerations

Oxygen Transfer--

Early reports from pilot plant work with Captor (20) indicated that PBSS significantly increase the efficiency of oxygen transfer for both coarse and fine bubble systems. This enhanced transfer may be ascribed to air bubble hold-up and attachment to the PBS particles as well as to interfacial transfer between the attached bubble and the active biomass surface. Reiber and Stensel (21) reported increases in oxygen transfer through a sparged fixed-film biological reactor, and attributed this transfer to both bulk liquid and interfacial transfer. Both laboratory and field work with PBSP are under way to evaluate this phenomenon and to quantify it more fully. Preliminary results from these tests indicate that the original claims were exaggerated.

Off-gas oxygen transfer tests under field conditions appear to be the most effective way to evaluate PBSS. Unfortunately, direct comparison with comparable suspended growth systems under identical conditions may be very difficult. In some configurations, gas flow rates required to hydraulically mix PBSP may be significantly higher than optimal for oxygen transfer. Furthermore, diffusion limitations by DO may require higher mixed-liquor DO concentrations than employed in conventional suspended growth systems (Section 5, page 43). Thus PBSP mixing and entrainment requirements, as well as higher DO requirements, may offset any gains achieved in oxygen transfer.

PROCESS CAPABILITIES, APPLICATIONS AND LIMITATIONS

The PBSS has been found to lead to the following advantages for treating wastewaters:

- Very high concentrations of biomass can be retained in the reactor, as compared with suspended growth systems.
- Biomass may be retained within the reactor, obviating the need for external biomass recycling.

- o Biomass may be recovered directly from the PBS particles, thereby reducing the solids loading to the clarifier.

- o The biomass recovered from the pads may be higher than that obtained from gravity settling and thickening.

These advantages suggest the following immediate applications of this new technology:

- o Upgrading existing overloaded treatment facilities, and
- o Pretreatment of high strength industrial wastes.

Current PBSS technology is considering a number of different reactor configurations. Table 17 presents the characteristics of four general reactor arrangements. These systems may be single units or may be staged in combination with other treatment processes. In general, PBSS reactors are mixed by air diffusion with fine or coarse bubble devices. Diffuser placements vary from one system to another, but are critical in providing proper PBSP distribution. PBSSs are designed with hydraulic configurations ranging from completely mixed to plug flow systems with aspect ratios as high as 10 to 1.

Details of reactor systems now being tested are described in Section 4.

The primary limitations to the current PBSS technology, as described in Sections 5 and 7, deal with:

- o PBSP distribution,
- o Presence of high suspended solids in the effluent, and
- o The need for a fundamental understanding of PBSP mechanisms which will lead to more effective modeling of the process.

DESIGN CONSIDERATIONS

The criteria for designing PBSS for wastewater treatment applications are currently being developed. Many of the important design parameters for these

TABLE 17. REACTOR CONFIGURATIONS FOR PBSS's AND THEIR CHARACTERISTICS

	Reactor type			
Characteristic	1	2	3	4
PBSP retained or removed	Removed	Removed	Retained	Retained
Biomass control	Squeezed	Squeezed	Attrition	Attrition
Effluent biomass recovery	None	Clarification	Clarification	None
Biomass wasting	Squeezed solids	Squeezed solids	Underflow	Effluent
Biomass recycle	No	Yes	Yes	No

systems have been identified and are outlined in Table 18. A brief discussion of a number of these parameters and their current status is presented below.

PBS Particle Characteristics

Both Simon-Hartley Ltd. and Linde AG have expended substantial time and money to develop PBS particles that are wear-resistant and that meet the requirements of their particular process. Reticulated or partially reticulated polyurethane (polyether) foams have been selected over polypropylene or polyester materials based upon the better wear-resistant properties of the former materials. High porosities are desirable, as described earlier, typically being between 95 and 97 percent. Pore size apparently affects total biomass hold-up, but insufficient research has been performed with wastewaters to indicate the importance of this characteristic. Simon-Hartley Ltd. feels that the 30-pore-per-inch size is optimal for its pad size and configuration. They feel that biomass hold-up is dependent upon the ratio of pad size to pore size.

TABLE 18. SELECTED PBSS DESIGN PARAMETERS

- PBSP characteristics:
  - Material, pore size, density, dimensions

- PBSP number/reactor volume
- Biomass hold-up
- Reactor MLSS (total)
- Biomass specific substrate uptake

- Reactor loading:
  - F/M
  - SRT
  - Volumetric load
  - Hydraulic residence time

- Air flow:
  - PBSP distribution
  - Oxygen transfer efficiency
  - Aeration efficiency
- Oxygen demand (SOUR)
- Reactor D.O.

- PBSP cleaning rate
- Biomass yield
- Sludge concentration

- Screen opening
- Screen hydraulic load

PBS particle dimensions depend to a large extent upon the need to handle the particle (i.e., to remove and clean them). A maximum diffusional dimension of about 6 to 8 mm has been adopted by both Simon-Hartley Ltd. and Linde AG. Currently Simon-Hartley Ltd. employs a 25 mm x 25 mm x 12.5 mm particle, whereas Linde AG has elected to go with cubes ranging from 10 to 15 mm on a side.

PBS Particle Number and Biomass Concentration

To date, PBS particle concentrations have been used in wastewater applications ranging from 10 to 40 percent by volume. Increasing particle concentrations increase potential biomass concentrations and concomitant volumetric rates of reaction. Unfortunately, upper limits on particle concentrations are dictated by basin hydraulics, which are, in turn, dependent upon basin geometry, diffuser type and placement and gas flow rate (current PBSS are all mixed by air). Upper limits on PBS particle concentrations in practice today range from 40 to 50 percent. Substantial research remains to determine optimal basin geometry, diffuser placement and gas flows for PBSSs.

As described earlier, particle biomass hold-up is dependent upon substrate concentration and characteristic particle pore size, hydraulic regime and cleaning rates. Wastewater characteristics and loading variations have also been implicated as potential controlling variables as well. Current experience of Simon-Hartley Ltd. with British wastewaters indicates that typical particle hold-ups range from 4 to 8 g/L (based on dry weight per gross particle volume) with an average of, perhaps, 6 g/L. Initial Simon-Hartley Ltd. design predictions were for particle hold-ups of 20 to 25 g/L. Linde AG predicts particle hold-ups ranging from 10 to 20 g/L.

Total reactor biomass concentrations are dependent upon particle biomass plus suspended biomass. Simon-Hartley Ltd. predicts typical reactor biomass concentrations in the 7,000 to 10,000 mg/L range (particle biomass only). Linde AG may expect concentrations ranging from 5,000 to 10,000, assuming particle biomass (10 to 20 g/L) plus suspended biomass (2 to 4 g/L).

Substrate Uptake/Loading

Currently, the loading parameter that best depicts PBSS performance is not well delineated. The fundamental independent variables that affect any biological treatment performance, namely, active biomass concentration, specific substrate uptake rate, substrate concentration/characteristics, dissolved oxygen concentration, temperature and pH, should affect PBSS. The mathematical form of the design parameters, however, is not yet clear. Currently, PBSSs are designed on the basis of BOD loading (mass/time, mass/volume, time) and hydraulic detention time (reactor volume/forward flow, reactor volume/forward + recycle flow). Initial Simon-Hartley design loadings of 4 to 5 kg BOD/m^3·d and a retention time of 45 to 60 minutes appear to be optimistic. Recent pilot plant work performed at the Water Research Centre indicate that a loading rate of 2 to 3 kg/BOD m^3· d is more reasonable, giving total BOD removals of about 50%. Linde AG design carbonaceous systems in the range of 2 to 3 kg BOD$_5$/m^3· d at residence times of 100 to 150 minutes. Additional research is needed to develop more definitive loading parameters for these systems.

Adding to the complexity of this performance parameter formulation is the contribution of suspended biomass to system kinetics (positive) and effluent quality (negative). This problem is not unique to PBSS's. Fixed-film and fluidized-bed systems as well as dispersed growth reactors produce dispersed solids that negatively contribute to effluent quality. Analytical procedures must be carefully specified in order to properly evaluate this contribution. The fraction of active biomass associated with the nonparticle suspended solids in the reactor will contribute in a positive fashion to substrate uptake. Unfortunately, the activity of this biomass fraction is likely different than that associated with the particle. (Diffusion limitions in the particle may or may not affect specific substrate uptake rates, and attrition or cleaning of particles may produce a disproportionately high amount of inactive biomass.) Clearly, suspended biomass contribution to reactor performance is more important in Type 2 and 3 reactors (Table 17).

Air Flow - Oxygen Transfer/PBS Particle Mixing

Currently, all PBSSs are mixed with diffused air. As discussed earlier, the mixing requirements of PBSSs are not yet well developed but are highly dependent upon mixing patterns within the basin. In order to effectively mix PBS particles within the reactor, a region of downward flow must be provided. Furthermore, in tanks that produce a more nearly plug flow condition, back mixing of pads countercurrent to influent flow must be provided in order to prevent a build-up of PBS particles at the effluent end of the reactor.

Currently, the Captor project team of Simon-Hartley Ltd. and the Water Research Centre are considering completely mixed tank configurations with diffusers placed such as to provide a region of downward liquid flow. Using a 25 m^3 test tank with an aspect ratio of 2:1, investigators at the Water Research Centre laboratories studied three distinct diffuser placement patterns:

- Longitudinal placement with all diffusers along one side occupying 25 percent of the bottom area.

- Longitudinal placement with all diffusers along one side occupying 46 percent of the bottom area.

- Transverse placement with all diffusers along the centerline occupying 26 percent of the bottom area.

Air flows required to achieved effective mixing of 36 pads/L for the three configurations above were 75, 133 and 141 L/m^2· min, respectively. Full floor coverage required air flows of up to 300 L/m^2· min. Linde AG uses a cross roll configuration in tanks of high aspect ratio operated as nearly plug flow reactors. Air flow rates in full-scale basins appear to be high, but particle distributions from influent to effluent end are fairly uniform. No technical design data are currently available from Linde.

Air is also provided to satisfy the respiratory requirements of the biomass. Although few measurements of specific oxygen uptake rate (SOUR) have been made for PBSSs, values reported range from 30 to 120 mg O_2/g hour. These are in the range of those reported for conventional activated sludge. Total oxygen requirements (mg/L/hr) for PBSSs, however, could be substantially higher than conventional suspended growth systems because of the higher active biomass per unit volume.

As discussed earlier, there is some evidence that oxygen transfer efficiencies of PBSS's are higher than suspended growth reactors with comparable geometry, diffuser placement and gas flow rate. These increases in efficiency are reported to range from 10 to 15 percent (Linde AG) and higher (Simon-Hartley Ltd.). Substantial attention must be given to quantifying these increases through off-gas analysis. Since air flow rates required to effectively mix particles may be higher than those for optimal oxygen transfer, it is likely that the advantage of increased efficiency may be substantially lost in PBSSs. Conservative design, assuming conventional transfer efficiencies, is warranted at this time until more definitive data are available.

Finally, in designing the oxygen transfer system, it is important to provide reactor dissolved oxygen concentrations that are sufficient to prevent diffusion limitations. Recent field experience at Freehold and at the Water Research Centre with pilot plants using carbonaceous removal systems, and by Linde AG with nitrification systems, indicate that specific rates of substrate removal are strongly correlated with dissolved oxygen concentration (Section 5, page 22). The high DO concentrations require higher air flow than needed for mixing pads in the the Captor carbonaceous configurations. Recent studies at Water Research Centre indicate air flow requirements in the region of 200 to 240 L/m^2· min for proper maintenance of dissolved oxygen.

PBS Particle Cleaning/Sludge Characteristics

Cleaning of PBS particles is an important feature of the Simon-Hartley Ltd. PBSSs. The mechanical design of PBS particle cleaners is now well developed (Section 5). The impact of particle cleaning frequency on PBSS performance is not well understood, however. Excessive cleaning appears to severely reduce particle solids and result in poor particle distribution (flotation). Little or no cleaning may result in excessive biomass build-up, diffusional limitations, and inert solids build-up in the particles. Simon-Hartley Ltd. recommends cleaning rates in the range of 10 to 20 percent per day (number cleaned/day/total number in system).

Intuitively, one would expect that an increase in cleaning rate would produce a younger, more active particle biomass, a higher sludge yield and perhaps a greater capacity of the particle to "mop up" dispersed suspended solids. Furthermore, it is theoretically reasonable to assume that the cleaning rate should be established at a point where no attrition will occur. Currently, there are insufficient data to show any relationship between cleaning rates and specific substrate uptake rates, effluent suspended solids, biomass activity (SOUR) and sludge yield.

Sludge solids concentrations obtained from PBS particle cleaners have varied with the generation of cleaner. The technology is now available to effectively drain water away from pads by gravity prior to the final squeezing. Under these circumstances, particle sludge concentrations in the range of 4 to 5 percent may be achievable.

The yield of biomass in PBSSs is not well documented to date. It is reasonable to assume that yield would be similar to conventional biological treatment systems. But again, the defining independent variables affecting yield in PBSSs are not yet known.

Screening

Screen openings are dependent upon PBS particle size. Currently, Simon-Hartley Ltd. has found that woven mesh, 4 mesh (5.13 mm aperture) works very well for the 25 mm x 25 mm x 12.5 mm PBS particles. Screens are sized to handle a wastewater flow of 78 $m^3/h/m^2$. It is imperative that PBSS's be preceded by adequate screening, however. Build-up of detritus escaping from primary processes can cause serious screen blockages in the PBSS if adequate prescreening is not provided. No data are currently available on Linde AG screens.

ENERGY ANALYSIS

The energy requirements for PBSS are probably very similar to those of conventional activated sludge systems. Currently, there are insufficient data to accurately assess energy differences that may exist. Basically, energy differences between these processes, if they exist, will be in providing mixing and oxygen requirements. As described above, the PBSSs may achieve higher oxygen transfer efficiencies than comparable suspended growth systems, but air flow requirements may be higher in order to effectively mix the particles. Particle cleaners will also consume some energy in the Type 1 and 2 processes (Table 17).

OPERATION AND MAINTENANCE REQUIREMENTS

Operational requirements for PBSS's are listed in Table 19. In general, they parallel requirements for activated sludge systems, with the exception of particle cleaning rates in Type 1 and 2 processes. Laboratory testing includes influent and effluent monitoring and reactor monitoring including particle biomass hold-up, particle distributions, SOUR, suspended solids, cleaner solids, dissolved oxygen, temperature and pH.

Maintenance of PBSS is also similar to conventional activated sludge systems (Table 19), with the exception of PBS cleaners and screens.

TABLE 19. PBSS OPERATION AND MAINTENANCE REQUIREMENTS

Maintenance	Operation
o Screens o PBS cleaner o Blowers o Diffusers	o Reactor D.O. o Pad cleaning rate (Type 1 & 2) o Sludge return (Type 2 and 3) o Sludge wasting o Influent/effluent monitoring o Reactor monitoring

COSTS

Cost data on PBSS are not well developed at this time. A detailed cost analysis performed by the Water Research Centre appears in Section 7.

SECTION 7

COMPARISON WITH CONVENTIONAL TECHNOLOGIES

GENERAL

The studies performed on porous biomass support systems to date have been aimed more at development than demonstration or evaluation. Lengthy records of steady-state performance under optimum or even near-optimum operations do not yet exist. The technology cannot be considered as satisfying the "fully developed" I/A criterion at this time. Some of the comparisons against conventional technologies which are normally called for in an assessment of this type are, therefore, premature. Nevertheless, comparisons will be attempted, using the existing data base, in seven general areas. These are:

1. Cost
2. Energy
3. Performance/Reliability
4. Environmental Benefit
5. Toxics Management
6. Joint Treatment Potential
7. Residuals Generated

Cost

Only two cost analyses of the Captor process have been prepared to date. One of these was by D. H. V. Wheeldon of the Water Research Centre in July, 1981 using third-quarter 1980 costs to compare Captor versus activated sludge for a new plant at the scale of 20,000 m^3/d (5.3 mgd). Two options were considered: a carbonaceous BOD removal system satisfying U.S. secondary treatment standards of performance, and a system capable of year-round nitrification. The assumptions used in that analysis were as shown in Table 20. Secondary clarifiers were assumed to be required for the Captor systems. With these assumptions, the conclusion was that the most significant cost element in a present worth analysis of Captor was the replacement rate of the pads. Captor was judged more cost-effective than a nitrifying activated sludge system when the pad replacement rate was less than 20 percent per year. Captor was more cost-effective than an activated sludge system designed for carbonaceous BOD removal when the pad replacement rate was less than 30 percent per year. It is interesting to note that current estimates of pad life are about 12 years, a replacement rate of 8.3 percent per year.

More information is, of course, available now, primarily from the Freehold study, which can be used to test the rest of Wheeldon's assumptions and perhaps expand the scope of the present worth comparison somewhat.

An economic analysis was also performed in connection with the planning for the Freehold study. This analysis, performed by H. Crabtree of the Severn Trent Water Authority, compared the addition of Captor as pretreatment in all

TABLE 20. PERFORMANCE ASSUMPTIONS - ECONOMIC ANALYSIS OF CAPTOR VS. CONVENTIONAL ACTIVATED SLUDGE

	Captor	Activated sludge
Biomass, g/L	9	3.5
F/M, kg BOD/kg-d		
Nitrification	0.15	0.15
Non-nitrifying	0.25	0.25
Aeration efficiency kg O_2/kwhr	1.8	1.8
Waste sludge conc. (%)	5	cosettled with primary sludge to 7
Pad replacement rate (%/yr)	0-100	N/A

five aeration basins to the addition of biological towers. Again, the conclusion was that Captor would be more economical than the nitrifying filters if the replacement rate of the pads was less than 20 percent per year.

Energy

Preliminary data on oxygen absorption in a Captor cell do point to probable increases over activated sludge designed for the same effluent quality. The few oxygen transfer experiments performed by Hegemann (1) using the Linpor foam elements also point to higher oxygen transfer; however, the increases found by Hegemann (about 10 to 15 percent) were much more modest than the increases reported from some of the early Simon-Hartley, Ltd. pilot-plant work. Until the performance of off-gas testing at the Freehold facility is completed, we are reluctant to quote specific figures relating to possible energy savings over conventional activated sludge. We are willing to state that there is no possibility of decreasing the efficiency of energy utilization by employing foam elements in an aeration basin. The quantity $\alpha K_L a$ will be at least as high as one would find in an activated sludge system of the same geometry and aeration system design.

Performance/Reliability

Porous biomass support systems have some unique characteristics which, under certain conditions, will provide greater performance reliability than equivalent conventional technologies. The qualifying conditions are important, however, because when they are not met, PBSS's may prove less, rather than more, reliable. First, preliminary and primary treatment systems must be designed and operated to protect the PBSS, especially against grease and solids, the latter of which can interfere with the hardware (pad cleaners in the case of Captor and retaining screens for both Captor and Linpor). Second, these processes do not seem to have special advantages for carbonaceous BOD removal from weak wastewaters. No "break-even" economic analysis has yet been performed to determine the approximate cross-over point (concentration of BOD) where PBSS's show advantages over conventional technologies, if such a point exists. With the conditions of at least medium-strength wastewater and good preliminary/primary treatment satisfied, the advantages of PBSS's are as follows.

For certain applications there is less, sometimes no dependency on secondary clarifier operation as a *sine qua non* to successful operation. This is especially important at high F/M loadings when the PBSS is being used as a pretreatment process. At high loadings the flocculation characteristics of activated sludges can easily be lost, producing a continual downward spiral of MLSS and, hence, treatment capacity. The data thus far indicate that a clarifier-related failure is highly improbable for a PBSS, whether it is used alone, as in Linpor-C, or used as pretreatment to activated sludge, as in Captor. At Downingtown, for example, the onset of filamentous bulking in the activated sludge system was not accompanied by a comparable problem in the Captor pilot plant. Filaments were observed microscopically in the system, but at low-volume concentrations, and they did not cause any problems. At Freising, using side-by-side comparisons on a wastewater definitely prone to cause filamentous bulking, the SVI values in the activated sludge sections showed excursions into the 500 mL/g range compared to 130 mL/g in the Linpor-C tank (see Section 5).

In addition to the inherent resistance to "bulking" problems, there is the improved reliability of the waste sludge stream taken by itself (for the Captor process). Although most of the development work to date has failed to reproduce the 4 to 5 percent solids concentrations achieved in earlier pilot-scale studies, there is little doubt that the potential to achieve these concentrations in practice does exist and will be realized in some systems, especially with continued improvement of the pad cleaning mechanisms. By way of comparison, the maximum potential waste solids concentration from an activated sludge process, in the absence of additional thickening, is generally conceded to be between 1½ and 2 percent. Even dissolved air flotation thickening of waste activated sludge cannot consistently produce a 5 percent float. In addition, a polymer is normally required.

There is also an improved reliability of PBSS's over activated sludge relative to their ability to handle "shock" loads (severe but temporary pertubations in concentrations, flows, or both together). PBSS's would show no advantages over trickling filters in this regard, however.

The advantages stated previously in this section can be taken as reasonably well-established fact. Given the potential economic advantages as well, an engineer might well ask whether activated sludge systems are on their way out, to be replaced by PBSS's wherever the two basic conditions are met. Careful analysis of the data, however, indicates that there are trade-offs to consider. In particular, a somewhat lower performance of PBSS's is indicated when compared against activated sludge at comparable F/M loadings. It is not correct to say that because you can maintain 8,000 mg/L of EMLSS in a PBSS and only 3,000 mg/L in a conventional activated sludge plant, that you can reduce the volume of the PBSS aeration basin to 3/8 of that required by the activated sludge for the same end point. Because of differences in physiological age and condition of the respective sludges, the PBSS is likely to show a slightly lower specific activity (substrate conversion rate in mg BOD/gram EMLSS-hr.). Only additional research will answer questions concerning the relative effectiveness of biomass in PBSS's as compared to activated sludge.

Environmental Benefit

PBSS's will involve less commitment of land then trickling filters, without the potential for odors or filter fly production, and with less commitment of land than activated sludge. There may be substantial environmental improvements when PBSS are used to retrofit an existing overloaded plant, since this is one method of upgrading which does not require extensive new construction or a lengthy disruption of normal treatment practices. Additional possible benefits are discussed in the next section.

Toxics Management

In general, there are probably no substantial differences relative to conventional technologies. An exception may exist where PBSS's are used as pretreatment processes for wastewaters which only occasionally show slugs of toxics, and in which the toxic materials tend to partition onto both the biomass and the pad material. From the Freehold studies it is known that Captor did provide protection for the downstream activated sludge process against the effects of three toxic discharges. Two known episodes of copper/nickel dumping and one of waste oil have been documented since the Captor study began at Freehold. The heavy metal discharges affected the control activated sludge system severely, and on the second occasion the sludge became so inactive that most of it had to be wasted from the system to reestablish activity. The activated sludge systems downstream from the Captor processes were not so affected. During the oil discharge episode it was found that the pads, being hydrophobic, had a natural affinity for the oil and sorbed most of it, preventing its escape to the downstream activated sludge process. Although difficulties were experienced with the pad cleaning operation because of the oil, the overall process stability was far better than that of the control, which experienced sludge settleability problems for some time after the discharge had occurred.

Joint Treatment Potential

No special advantages are seen at this time relative to conventional technologies in terms of process capability, except as noted in the Performance/Reliability section above, for cases where the industrial wastewater component tends to produce filamentous bulking. An economic advantage should certainly be gained whenever the flow diagram of Figure 22 can be employed. In the diagram, a strong industrial waste is pretreated, using Captor, and the concentrated waste sludge is diverted to the same sludge treatment system used for the domestic waste sludges. Joint biological treatment (of any sort, including perhaps the use of Captor) is provided for the combined effluent.

Residuals Generated

For a comparable level of treatment, the dry weight of sludge generated in a PBSS will be practically identical to that produced by any conventional process. The advantage will lie in comparison of the wet volumes generated relative to activated sludge. Both dry weights and wet volumes will be closely comparable to the trickling filters.

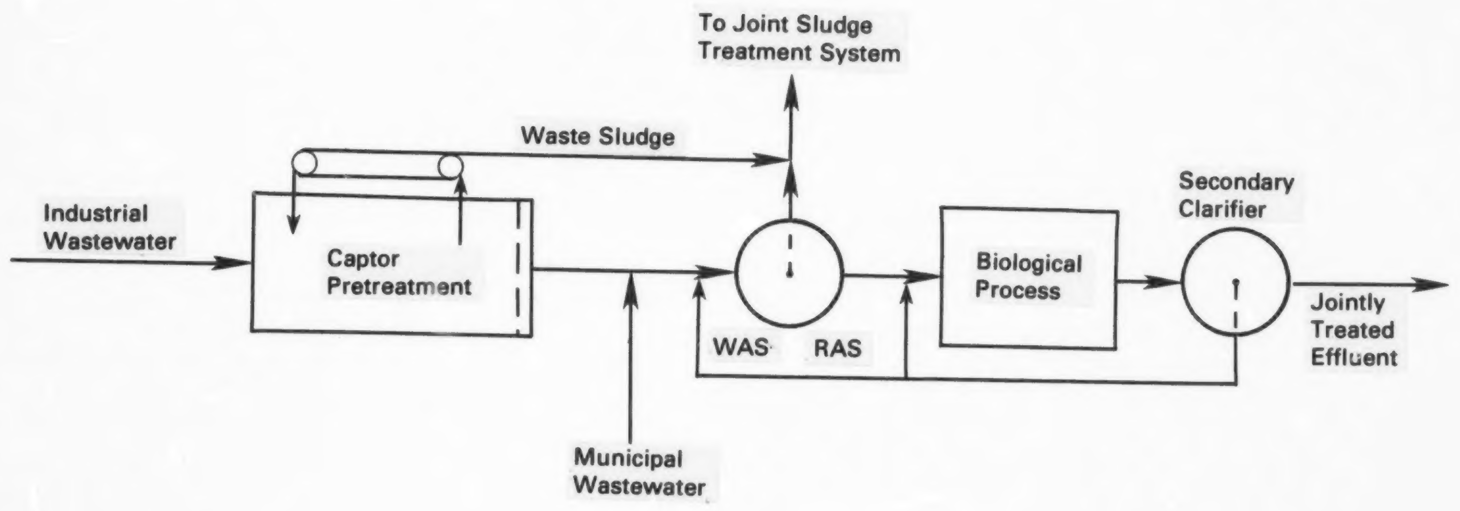
To Joint Sludge
Treatment System
Waste Sludge
Industrial
Wastewater
Captor
Pretreatment
Secondary
Clarifier
Biological
Process
Jointly
Treated
Effluent
WAS
RAS
Municipal
Wastewater

Figure 22. A joint industrial - domestic flow diagram indicating potential economic advantages.

SECTION 8

NATIONAL IMPACT ASSESSMENT

PRESENT AND FUTURE MARKET

The primary market areas for porous biomass support systems appear to fall into two categories. The first is for upgrading of existing secondary plants, primarily those using activated sludge or one of its modifications. PBSS's might be considered as an add-on to the front end to attain compliance in carbonaceous BOD removal or as an add-on to the rear end to provide nitrification. It is known from summary reports (1, 2) that approximately 25 to 30 percent of all municipal and industrial secondary treatment plants in the U.S. are experiencing significant problems in meeting their permit conditions. Further, there were about 10,300 secondary and advanced secondary municipal treatment plants and over 40,000 industrial treatment plants operating in 1982 (3). The number of municipal plants in these categories is expected to increase to about 18,400 by the year 2000, primarily through upgrading of existing primary plants to secondary status. These numbers indicate that a tremendous market exists for inexpensive and reliable upgrading techniques, and PBSS's certainly represent one approach for supplying this need.

The second large potential market is for pretreatment of industrial wastewaters, especially high-strength ones, for a variety of reasons. Some specific applications would be the following uses of the PBSS technology:

1. Before discharge to municipal sewers to decrease user charges.
2. Before land treatment systems to provide a low-cost "roughing" treatment, alleviating problems with biological clogging of the

infiltrative surface while conserving heat (important for cold-temperature operation).

3. Before RBC units and biological towers, with plastic media to reduce growth on these units and avoid structural failures.
4. Before activated sludge systems operating at high F/M ratios, to alleviate filamentous bulking problems.

MARKET PENETRATION POTENTIAL

The extent to which porous biomass support systems penetrate the broad market available in the U.S. will probably depend on the future success of demonstration projects that are on-line or planned for the near future. Past efforts to prove the value of Captor in the U.S. have not been particularly successful (see page 28), and the more successful experience in the U.K. (see page 41) has, until this assessment, been withheld from potential users in the U.S. Similarly, the more promising data from Linpor systems being tested in West Germany has not reached the U.S. as yet. At this point in time, very few U.S. engineers have even heard of PBSS's, and among those that have, there is a great deal of understandable skepticism regarding its potential. Given the limitations of the U.S. pilot-plant trials at Marion, Illinois and Downingtown, Pennsylvania, and the quality of the data generated at these installations, an engineer would have to be relatively optimistic to commit to Captor or Linpor without some pilot-plant work. Potential users of PBSS's will often be constrained by budget, time-frame or both, and forced to choose from among those processes which appear to have no risk associated with them.

RISK ASSESSMENT

A rational evaluation of risk must begin with the proviso which was discussed on page 81--there must be adequate preliminary and primary treatment of the wastewater to remove materials which can physically interfere with pad cleaning (Captor) and retaining screens (Captor and Linpor). Failure to provide adequate facilities at the head end of the plant will result in a substantial risk of system malfunction and can be considered a minor disadvantage of PBSS technology as compared with some, but not all, conventional technologies.

The first area with some associated risk is that of the mixing characteristics of the aeration system. Although guidance is rapidly evolving through the pilot and field studies, there presently are no infallible design guidelines to guarantee proper pad mixing and distribution. Given the importance of these aspects of operation, this is a serious deficiency, especially when considering the adoption of PBSS technology in an existing aeration basin. The owner cannot always be expected to bear the costs of optimizing mixing patterns by trial and error. Another area of risk is the uncertainty of the role of secondary clarification when a PBSS is used alone and not coupled to a downstream activated sludge process. There are not enough full-scale results upon which to confidently size a clarifier for all the process modifications which might be considered. Omission of a secondary clarifier from a process flow scheme utilizing Captor as the sole biological treatment process would be a serious mistake at this stage of process development. Although claimed or implied as an advantage of Captor in some early literature on the process, omission of a secondary clarifier is definitely not recommended at this time. Exceptions are noted for industrial pretreatment and perhaps also for nitrification. On the other hand, pilot plant experience in West Germany with Linpor N indicates that this process may succeed without the use of final clarifiers. Less risk would be associated with I/A funding of full-scale demonstrations of this concept.

Some areas of minor risk which need to be addressed in further research programs include the impact of DO concentrations on process performance, the effects of certain biological growths (i.e., fungi) on PBS particles with respect to pad cleaning and biological activity, and factors affecting biomass yields from these processes.

Although these areas of risk are of concern and require additional study and development, they should not be allowed to jeopardize the evolution of the technology. As described in previous sections of this report, there are several inherent advantages of PBSS technology, some already demonstrated and some potential but not as yet demonstrated. The technology has proven successful in certain specific applications, for example:

1. Industrial wastewater pre-treatment
2. Upgrading an activated sludge system plagued by high SVI
3. Nitrification

On the other hand, the technology has not fulfilled all of the expectations of its developers. For example, it seems poorly suited for use with weak wastewaters when nitrification is not an objective and has not been capable of meeting effluent objectives without a final clarifier when employed as the sole biological process unit.

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